CHLORINATED HYDROCARBONS: THEIR DYNAMICS AND EGGSHELL EFFECTS ON HERRING GULLS AND OTHER SPECIES

BY
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To Professors: Hickey

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This thesis having been approved in respect to form and mechanical execution is referred to you for judgment upon its substantial merit.

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CHLORINATED HYDROCARBONS: THEIR DYNAMICS AND EGGSHELL EFFECTS IN HERRING GULLS AND OTHER SPECIES

A thesis submitted to the Graduate School of the University of Wisconsin in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

by

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PREFACE

The research reported in this thesis involved diverse, but related topics. The rapid changing nature of pesticide research--or now more accurately because of the recent discovery of PCB's, chlorinated-hydrocarbon research--has required that new hypotheses be developed and tested during the course of studies already in progress. My advisor, Joseph J. Hickey, has had a constantly fresh approach to research topics, providing new ideas as well as allowing me free reign to explore my own ideas. Necessarily, reference to the research reported here can only be honestly reported in terms of plural authorships. I have therefore included within this thesis all coauthors in the belief that today's research must essentially be a teamwork effort; it would be naïve to think otherwise.

The first topic to be presented, kinetics of chlorinated hydrocarbons in Lake Michigan Herring Gulls, was developed at an informal meeting in Dr. Hickey's hotel room during the 1965 North American Wildlife and Natural Resources Conference. There, colleagues from the U.S. Fish and Wildlife Service, Audubon Society, and University of Wisconsin discussed various aspects of wildlife-pesticide problems. J. J. Hickey and J. A. Keith had already demonstrated that Lake Michigan Herring Gulls were badly contaminated with metabolites of DDT, and Keith, under Hickey's supervision, demonstrated adverse effects of such residues on the reproduction of the Green Bay gulls. The basic hypothesis we tested was whether the very high residues observed in wild adults could be attained within one year in relatively lightly contaminated juveniles that had been fed Alewives, their main food-source in the wild. Residue concentrations in whole Alewives were about 1000 times less than those found in the fat of wild adults.

We continued to monitor Lake Michigan Herring Gulls and Alewives in the years following our feeding experiment. A major research problem developed after the completion of the feeding experiment: the interpretation of chromatograms for insecticide residues in the presence of PCB's. This required nearly complete reevaluation of our residue data and it delayed our final results for about two years. Satisfactory analytical techniques for the precise quantification of PCB's are only now (1970) beginning to emerge.

A major discovery in the field of pesticide ecology, that of D. A. Ratcliffe in 1967 in Great Britain, changed the direction of our research toward eggshells and calcium deposition. Ratcliffe, by examining museum specimens, found a significant change in the eggshell thicknesses of three declining species of British raptors, generally beginning in 1946 or 1947. J. A. Keith had observed a high frequency of broken eggs on Green Bay gulleries in 1964 and we saw the same phenomenon in later years. Related phenomena--egg eating, egg breakage, and egg disappearance--had all been reported for the Peregrine Falcon, the species which initially received the most attention because it had exhibited the most alarming recent avian population crash in this century. Many of the significant ecological events since 1947, when DDT had achieved general, public use, began to come together in a Madison conference convened by J. J. Hickey in 1965. I feel strongly that the "Peregrine Conference" has been a major stimulus to many of the significant findings in pesticide ecology for the past five years.

The feeding experiment completed in 1967, we followed up Ratcliffe's study in North America and examined avian eggshells in a large portion of the museums and private egg collections on the continent. For our early start, D. A. Ratcliffe deserves the credit. Of course, we included the

Herring Gull. The eggshell study was necessary to aid in determining some of the possible mechanisms of reproductive failures in Lake Michigan Herring Gulls as they might fit into other interactions observed in the wild. We had originally planned to study the eggshells of 11 raptorial species, 6 fish-eaters, and 2 species believed to be stationary in numbers (to serve as controls). The list was extended to 25 species to include other species already under study by colleagues in other parts of the country. We tested the hypothesis that eggshells had become thinner since the "era of the chlorinated hydrocarbons", the decade of the 1940s and later.

Because egg collecting had died out in the late 1930s, our original plan was to describe normal geographic variation in selected species to give future workers bases of comparison with present-day eggshells. Unexpectedly, we found many active collectors still in operation and our eggshell study was expanded from an original proposal of four months and 24 museums to a year and a half and some 90 separate collections. We needed more time to search out recent specimens once we knew they were available. Such specimens provided us with adequate materials to at least partially describe the presence or lack of eggshell changes in some of the 25 species we had planned to study. The greatest majority of egg collectors we contacted proved to be extremely helpful and cooperative.

This thesis is, then, divided into three major parts along with an appendix of miscellaneous data and publications relating to our research. Each section is written in the appropriate journal style and manuscript pages are shown on the lower right-hand corners of each thesis page. Eventually, all the papers here will be published in various journals.

The parts are as follows: (1) basic pesticide dynamics in Lake Michigan Herring Gulls, to be submitted to The Journal of Applied Ecology, (2) studies of normal and abnormal variation in the eggshells of North American Herring Gulls, to be submitted to The Auk, and (3) studies of eggshell changes in certain North American birds, to be presented to the Proceedings of the XV International Ornithological Congress. The appendix includes: (1) geographical variation studies in the eggshells of Common Loons, accepted by The Canadian Field-Naturalist, (2) eggshell studies in Brown Pelicans, published by the Wilson Bulletin, and (3) our initial results in Science.

I cannot acknowledge enough the encouragement and stimulus from my good friend and respected collegue, Joseph J. Hickey. Dr. Hickey provided me with unlimited opportunity to further myself, and for that, I am sincerely grateful. Dr. Hickey's youthful enthusiasm in research has maintained him as a leader in his field. R. W. Risebrough, J. A. Keith, and J. O. Keith were occasional field companions as well as sources of intellectual stimulation and aid. Many other coworkers and research aids are mentioned in the acknowledgements of the separate papers. Lucille F. Stickel and E. H. Dustman were our primary contacts and aids from our supporting agency, the Bureau of Sport Fisheries and Wildlife, Patuxent Wildlife Research Center, Laurel, Maryland. I am indeed grateful to the bureau. Had they not funded us, our research would not have been possible.

I must mention the names of individual persons who significantly aided us and helped us to expedite our eggshell data collection. I just wish I could mention their names in each publication: W. G. Abbott, G. D. Alcorn, D. Amadon, O. A. Austin, Jr., J. L. Baillie, A. M. Bailey, Laura B. Bailey, R. C. Banks, E. R. Blake, W. J. Breckenridge, D. B. Bull, T. J. Cade, J. M. Campbell, the late C. E. Carter, R. G. Chaffee, J. Cope,

J. L. Diedrich, J. B. Dixon, H. H. Frost, A. Ganier, R. C. Hallman, W. C. Hanna, W. G. F. Harris, Ed N. Harrison, W. W. Hill, N. D. Hoy, L. G. Izard, J. R. Jehl, Jr., N. K. Johnson, P. A. Johnsgard, R. B. Lyle, G. H. Lowrey, Jr., T. C. Meitzen, R. M. Mengel, R. T. Orr, E. P. Odum, K. C. Parkes, K. E. Pauley, R. A. Paynter, Jr., R. S. Palmer, S. B. Peyton, R. J. Pickering, M. Pollock, R. Quigley, R. W. Quillan, A. L. Rand, C. H. Richter, W. A. Squires, W. R. Spofford, E. A. Stoner, Ellie Stickney, H. O. Todd, Jr., the late W. E. C. Todd, A. Wetmore, and L. R. Wolfe.

Many of my staff contacts at Wisconsin have influenced my thinking, though probably unknowingly. G. Cottam, J. T. Emlen, Jr., O. L. Loucks, R. A. McCabe, and J. C. Neess were on various committees in my behalf. Finally, I wish to acknowledge my fellow graduate students, who were more than beer-drinking companions. From them I have had many informative and professionally stimulating hours of discussion.

I cannot say that pesticide research has been overly encouraging, though far from uninteresting. Many wildlife problems are now deeply associated or potentially associated with industrial and agricultural pollution. Many of our problems in wildlife conservation have always been tied with agricultural practices and in a sense always at the mercy of industry and agriculture, whether it be mining, grazing, farming, land-clearing, drainage, etc. Now, with environmental pollution, our field has received yet another aspect of competition. Despite the strong evidence for the potential or real hazards to wildlife and natural systems, our society's leadership seems generally unresponsive to sound ecological thinking and practice. I am fast coming to believe what Aldo Leopold said: "As for diversity, what remains of our native fauna and flora remains only because agriculture has not got around to destroying it." I would say that this applies as well to industry. Overexploitation of our environ-

ment continues to be man's primary goal whether directly or via side-effects. Rather than making a conservative living, we still insist on maximum and selfish exploitation with short-term goals. I can see this in my experiences. Supposedly responsible scientists even deny the adverse ecological effects of chemical pollution; or even worse, accept losses of diversity or potential losses as compatable with the "philosophy of progress." We have it in our own ranks. I am reminded of the pheasant biologist whose main goal was to "naturally farm" pheasants solely for the purpose of harvest. He failed to observe eggshell thinning in pheasants and on this basis concluded that wildlife was not suffering the adverse effects of pollution. His ecological world was limited to a "pheasant's viewpoint." Another of our ecologists counts blackbirds, Starlings, and White-tailed Deer and, finding that numbers are as high as ever or higher, concludes that wildlife has not been adversely affected by chemical pollution. Some even conclude from such data that wildlife has even benefited from the use of chemicals. Perhaps a conservative approach to natural ecosystems and man's role in them is needed. Overexploitation and destruction of diversity are far from conservative.

Daniel W. Anderson
13 August 1970

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PART 3. EGGSHELL CHANGES IN CERTAIN NORTH AMERICAN BIRDS.

PART 4. APPENDIX, A COLLECTION OF MISCELLANEOUS PAPERS RELATING TO THE GENERAL TOPIC OF THE THESIS.

captive herring gulls taken from the wild shortly before they attained the powers of flight.

Attention in this paper has been concentrated on p,p'-DDE, the now universally distributed metabolite of p,p'-DDT (1,1,1-trichloro-2,2-bis [p-chlorophenyl]ethane) in the world environment. This compound is known to be significantly involved in changes in eggshell thickness in North American herring gulls (Hickey and Anderson 1968) and has been found to produce these changes in mallards (Anas platyrhynchos) fed 3 ppm (wet weight) under controlled conditions (Heath et al. 1969).

STUDY AREAS AND METHODS

Collections and feeding trials

We collected 146 prefledging juveniles in early July 1966 from the breeding colonies in Green Bay and transported them to the Wisconsin State Game Farm, Poynette (Fig. 1). Five newly fledged juveniles were shot on 3 August 1966 to obtain initial data for the feeding trials; and ten adults were shot on 31 May as a starting point for the field observations, which included collections of wild adults at 2-month intervals. Approximately 39,700 kg of Lake Michigan alewives (Alosa pseudohanengus) were purchased from commercial fishermen in 2 batches (batch 1, May 1966; batch 2, August 1966; Table 1). They were glazed with water and stored at -20°C.

Juveniles were individually color-banded and randomly placed in 3.7-m by 3.7-m outdoor breeding pens, five birds per cage. Two water troughs (each 17 liters) were placed in each cage and cleaned and filled daily until freezup. During the winter months, we found that snow and moisture from food provided the birds with adequate water. The

SEASONAL VARIATION OF CHLORINATED HYDROCARBONS IN LAKE MICHIGAN HERRING GULLS

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This paper reports on the seasonal variation of some insecticidal residues in wild, adult herring gulls (Larus argentatus), their build-up in a captive population of young birds over the course of 322 days and their relationships to changes in the lipid content of the avian body. Some approximations of changes in the levels of apparent polychlorinated biphenyls (PCB's) are also included.

Wet-weight residue levels of p,p'-DDE (1,1-dichloro-2,2-bis[p-chlorophenyl]ethylene) have been reported as high as 2,800 ppm in the fat of a bald eagle (Haliaeetus leucocephalus) in California (Hunt 1969) and 5139 ppm in the fat of a herring gull collected in Wisconsin by J. A. Keith (personal communication 1964); but the dietary intake necessary to produce such levels remains to be characterized. On the basis of a small, known-aged sample of Lake Michigan herring gulls, Hickey et al. (1966) postulated that the major residue build-up in these birds occurred in their first year of life. However, the migratory habits of herring gulls at this age ruled out the possibility of relating this build-up to residue levels in the ecosystem of a single region. In the present study, we have sought to test the possibility that high levels of DDE can be accumulated by birds exposed to a steady diet of about 5-6 ppm of this compound and related compounds. This test was carried out by feeding Lake Michigan fish to a group of

FIG. 1. Map of the general study area in which herring gulls were sampled for chlorinated hydrocarbon residues in 1966 and 1967.

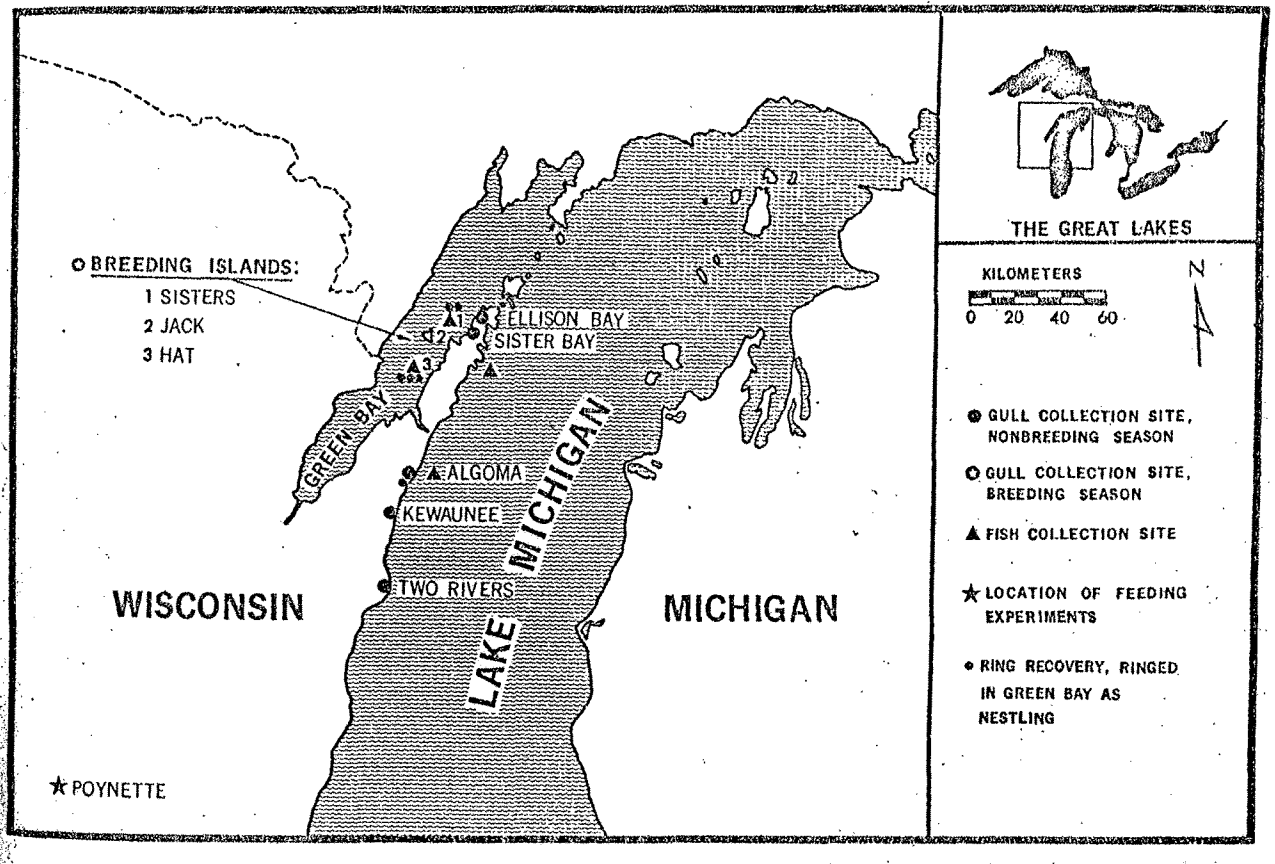


Table 1. Size of alewives and their pesticide residues (ppm fresh-weight), used in feeding trials with herring gulls

Measurement	Food item: Alewife-batch 1*	Alewife-batch 2*
No. pools analyzed	5	3
% water**	72.2 (70.5-75.3)	67.4 (66.3-69.0)
% fat**	6.4 (4.8-7.8)	12.1 (11.0-13.2)
Fresh-weight (g)/fish	27.7 ± 0.4	31.6 ± 0.6
Mean length (mm)/fish	160.2 ± 0.9	164.1 ± 1.2
ppm p,p'-DDE	3.41 ± 0.17	3.05 ± 0.65
ppm p,p'-TDE + p,p'-DDT	2.55 ± 0.20	1.56 ± 0.31
ppm apparent PCB	1.84 ± 0.34	2.07 ± 0.44
micrograms DDE/fish	94.4	96.4
micrograms TDE + DDT/fish	70.6	49.3
micrograms APCB/fish, A1254 equivalents	51.0	65.4

* Values given are means ± 1 standard error, unless otherwise noted.

** Based on pool means, values in parentheses are ranges.

feeding trials ran from 3 August 1966 to 20 June 1967. Fresh, prethawed alewives were fed (up to ten fish/bird/day) as determined by the consumption for the previous feeding, occasionally leaving excess. Alewives left from the previous feeding were counted whole or in portion and then removed. This was done every one to four days, depending on weather conditions (cold weather), which in turn dictated the length of preservation of the fish and their acceptability by the gulls. The alewives we used were relatively standard-size (Table 1) and, based on length criteria (Norden 1966), were all in age class III. We recorded number of fish consumed during each period between feedings and later converted the values to an estimate of biomass consumed.

Residue analyses were conducted each month on pools of 25 randomly selected fish taken from the current food of the gulls (Table 1) and combined with the biomass-consumed data for an estimate of residue intake. Five birds were sacrificed each month, and all birds were weighed at one-month intervals. Only groups that appeared healthy and were consuming amounts of food comparable to the mean for the entire colony were considered in this sacrifice. In adjusting the gulls to captivity and a diet of alewives, we initially encountered an outbreak of avian aspergillosus that killed 32 birds. Apparently triggered by the individual or cumulative stresses of capture, transportation, confinement and malnutrition (Friend and Trainer 1969), this epizootic was cleared up by adding 26 g of beef heart per week to each bird's diet for the duration of the experiment. This meat averaged <0.2 ppm (wet-weight) of total chlorinated hydrocarbons.

Treatment of carcasses

Both dead adults and juveniles were completely plucked after fresh body weights and plumage characteristics had been determined. Esophageal and stomach contents of wild-collected adults were removed and examined. The major and minor pectoralis muscles were removed from the left side of each bird for a separate breast-muscle analysis. Equal amounts of mesenteric and subcutaneous fat (1 to 2 g of each) were pooled from each bird as a fat sample for pesticide analysis. Heads, tails, feet, and wings were removed from the carcasses after breast and fat sampling, and these carcass samples, corrected for removal of one breast and 2-4 g of fat, were the basis of our "whole-body" determinations of pesticides as well as our fat indices. All samples were wrapped in aluminum foil, sealed and frozen (-23°C) until analysis 1-2 months following preparation. Just prior to analysis, each carcass and breast sample was ground and homogenized to a paste in a blender and then subsampled for fat and water extraction as well as for pesticide analysis. The fat samples and homogenized subsamples were ground in sodium sulfate prior to extraction.

The five juveniles (sexes combined) from each month's sampling were pooled for single analyses except birds from the last sacrifice group, which was run on an individual basis. Our wild-collected samples were run on an individual basis in every case.

Chemical analysis

Since residue analysis for p,p'-TDE (1,1-dichloro-2,2-bis[p-chlorophenyl]ethane) and p,p'-DDT is significantly interfered with by PCB's in standard, routine gas chromatography (Jensen 1966, Widmark

1967, Holmes et al. 1967, Risebrough et al. 1969, Koeman et al. 1969, Reynolds 1969), and since our original analyses were performed before these problems became apparent, we chose to reevaluate our original findings concerning DDT, TDE and suspected, apparent PCB residues.

All residue analyses and sample extractions were conducted by WARF Institute (hereafter referred to as WARF), Madison, Wisconsin. We have previously described the general laboratory procedures used for us by WARF (Hickey & Anderson 1968, Anderson et al. 1969), based on various combinations of the gas chromatography (GC) methods outlined by the U.S. Food & Drug Administration (1965-68), Risebrough et al. (1969) and Reynolds (1970). Dieldrin (not less than 85% of 1,2,3,4,10,10= hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-1,4-endo-exo-5,8= dimethanonapthalene) residues were removed by florisil cleanup.

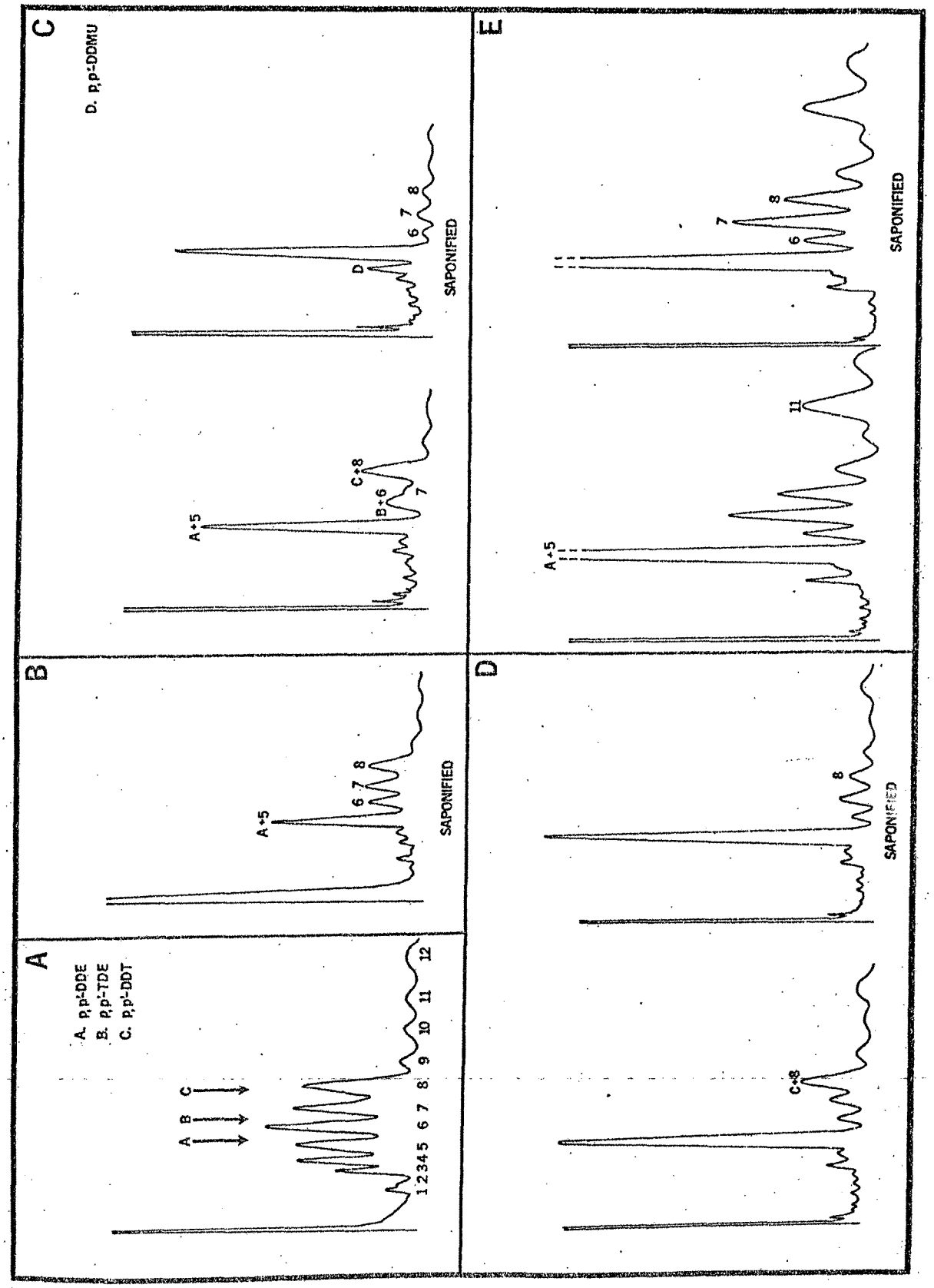
The presence of p,p'-DDE was confirmed by WARF (D. L. Hughes, personal communication 1967) in seven randomly selected extracts representing brain tissue, carcass homogenates, breast muscle and alewives by thin-layer chromatography. It can be seen from the GC chromatograms in Fig. 2 that some interference between DDE and PCB is possible. Peak-height (PH) comparisons in all Lake Michigan samples showed DDE to be very high in relation to peak 5, and we do not believe that such interference significantly altered the DDE data. In addition, DDE quantifications were always performed at high dilutions (possible because of its high concentration) so that interference from peak 5 was reduced to a minimum. Semiquantitative estimates of DDE, where possible, by thin-layer chromatography suggested that the levels were in general agreement with gas chromatography, our major source of

residue data. However, DDT and TDE were either not detected by thin-layer chromatography, or suggested to be much lower than gas chromatography alone indicated, especially in herring gull tissues. Two small, unidentified spots appeared on the thin-layer plates which were suspected to be PCB's. Analyses of PCB's by thin-layer chromatography have been shown to result in only a few spots, although most PCB's are mixtures of many different but related compounds (Lichtenstein et al. 1969).

Our estimations of PCB-like compounds were based on standards of Aroclor 1254 (Monsanto Chemical Co., trade name), expressed as "A1254 equivalents". The selection of A1254 (Fig. 2a) was based partially on the findings of Risebrough et al. (1969) and others (reviewed by Reynolds 1970) who found that of the commonly used Aroclors, the chromatographic pattern of A1254 (and that of A1260) most closely approximated those of field specimens on several columns. Likewise, we found a close resemblance to A1254 in the chromatographic patterns of our field specimens when they were compared to A1242, A1248 and A1254. Bagley et al. (1970) have positively identified PCB's in bald eagles by mass spectral analysis and have demonstrated that most were identical to the PCB's found in Aroclor 1254. Veith and Lee (1970) showed that Lake Michigan waters and fish contained predominant and "apparent" Aroclor 1254 mixtures, confirming the presence of PCB's by 3 methods: (1) comparative retention times of various peaks under different analytical conditions, (2) infra-red spectrophotometry and (3) mass spectrometry.

Our objectives in apparent-PCB quantification were not as much

FIG. 2. Tracings of chromatograms of extracts of various tissues as seen on the DC-200. A. Aroclor 1254 with peaks numbered as discussed in the text. Arrows show the positions of the major DDT-family residues. B. Saponified extract of a mixed garbage sample taken from a gull which was shot while feeding in a dump. Peaks 6, 7 and 8 did not change after saponification. C. Alewife extracts before and after saponification, showing interference of peaks 6 and 7 with p,p'-TDE. D. Juvenile herring gull fat extracts before and after saponification. E. Unsaponified and saponified extracts of an adult herring gull carcass homogenate, showing the nearly undetectable residues of p,p'-TDE and p,p'-DDT and the stability of the apparent PCB peaks 6, 7 and 8. Peak 11 suggests the presence of another compound not prevalent as seen in A1254, possibly representative of accelerated accumulation of a higher number, or mixture from A1260. In some instances, p,p'-DDE is off-scale and shown with dashed lines; in others, it is shown out of the linear range of response of the electron-capture detector. In all cases, DDE was quantified by a separate dilution. Slight discrepancies in retention times between the various chromatograms represent slight day-to-day variations in operating conditions.



toward quantitative precision as they were toward internal constancy of estimates, so that comparisons with other residues within the system we studied could be made and so that temporal comparisons of apparent-PCB's could be obtained (see Risebrough et al. 1969). They are identified in the same units as the other residues, but it should be understood that they may be less precise or inaccurate by some unknown constant. We did not attempt to identify any specific Aroclors by pattern resemblances and doubt that any single Aroclors compose the sole apparent PCB residues in any of our samples.

Greater toxicity of the lower molecular-weight, more volatile, lower-chlorine-content compounds in PCB mixtures is known to occur to house flies (Musca domestica) and Drosophila melanogaster (Lichtenstein et al. 1969). One might expect a greater biological degradation rate of such compounds under field conditions. Jensen et al. (1969) suggested that the lower-number (lower chlorination) PCB components are probably excreted or metabolized at a greater rate than the higher numbers, thus resulting in food-web concentration of the higher numbers. Degradation of certain of the earlier retention-time compounds in A1254 (QF-1 and DC-200 columns of gas chromatographs) has been reported for mallards (Anas platyrhynchos) by Risebrough et al. (1970). Our estimates of apparent PCB's based on A1254 assumed a relationship between their total amounts and the later-retention-time peaks 6, 7 and 8 (Fig. 2).

In the rereading of our earlier chromatograms from prior to WARF's use of saponification, p,p'-TDE, p,p'-DDT and apparent PCB's were estimated on the basis of various correction factors (CF's). Based on the data of Jensen et al. (1969) regarding degradation, we tested the

hypothesis that peaks 6, 7 and 8 were different in relation to one another between the various sample levels (Table 2, col. 1) but not between the tissues in any level. Statistical analysis substantiated this ($P < 0.001$) when randomly selected examples of the various classes of samples were reanalyzed with saponification to remove DDT and TDE (Table 2). All three corresponding peaks in A1254 standards remained unchanged after saponification. Peak 7, according to the ratios given in Table 3 and compared to standards, in our samples appeared to be relatively the most stable of the three in such biological materials. The differences, then, were used for the first correction factor determination, CF1 (Table 3, col. 7). Total PH6 + PH7 + PH8 in Aroclor 1254 was considered as 100 percent of CF1. PH7 was found to be measurable in nearly all instances on the DC-200. Interference of peaks 6 and 7 with p,p'-TDE in some fish pools (Fig. 2) caused difficulty in measuring PH7 accurately; therefore, the apparent PCB determination in these samples was estimated only after saponification revealed its true height. The peak height ratios of 6/7 and 8/7 were multiplied by the PH7 of standards (32.2 percent of peaks 6, 7 and 8 as determined by actual height measurements in many standards). They were then added to .322 for each respective sample level to obtain CF1.

Peaks 6 and 8 interfered with p,p'-TDE and p,p'-DDT, respectively (Fig. 2). Peak 7 did not interfere with any of the DDT-family residues, and its PH was used to determine the expected PH6 and PH8 in chromatograms of unsaponified extracts. The ratio differences given in Table 3 (cols. 3 to 6) for each of the different sample levels were the bases used to determine the expected ratios. Differences between the peak heights in saponified and unsaponified extracts were assumed to

Table 2. Comparisons and statistical differences between the three major peaks of PCB-like compounds in saponified extracts of various Lake Michigan sample classes as compared to A1254 standards

		Sample level			
Variable	Standards	Whole fish	Juvenile gulls	Gull eggs	Adult gulls
No.	14	9	10	17	10
Peak ratio (6:7)	1.20	0.67	0.58	0.50	0.46
Differences*	A	B	C	D	D
				0.48***	
Peak ratio (8:7)	0.91	0.77	0.73	0.74	0.71
Differences*	A	B	CB	BCD	BCD
			0.74***		
CF1	1.000	0.775	0.746	0.715	0.715
CF3**	7.34	5.69	5.47	5.25	5.25

* Differences not significant at the 99% level share a common letter, and were determined by the least-significant-difference-test and analysis of variance (Steel & Torrie 1960:106-107, 112-115). These relationships did not change at the 95% level.

** CF2 = (Conc. A1254 injected/Conc. DDT injected) X (PH DDT/PH7), CF3 = CF2 X CF1.

*** These ratios were combined on the basis of nonsignificant differences.

represent DDT and TDE. The estimations based on rereading original chromatograms were in agreement with values based on later saponification of the same extracts ($r = 0.95$, $P < 0.001$).

The major, apparent PCB peaks were crudely estimated on the basis of PH7 and on differences in sensitivity of equal volumes of A1254 (peak 7) and DDT standards at a given attenuation on the gas chromatograph. Peak 7 was quantified as though it was p,p'-DDT, and small differences between the actual PH7 and PH DDT standard were adjusted (Table 2). The calculated CF2 values from nine chromatograms each of the two standards, injected at different times and at different volume-pairs in the linear range of response averaged 7.34 (S.E. = 0.17, C.V. = 7%). A final CF, CF3, was calculated for each of the four sample levels (Table 3, col. 8) and a PCB-index determined for each analysis: apparent PCB (Est. ppm, A1254 equivalents) = CF3 X Peak 7 measured as DDT.

Dieldrin residues were detected in all the samples (10) specifically tested for that compound, but at low levels in comparison to the other chlorinated hydrocarbon residues. In herring gull fat samples in May 1966, dieldrin composed 0.19% of the total chlorinated hydrocarbon load. Reinert (1970) found that low levels of dieldrin were present in all Lake Michigan fish analyzed. In further discussion here general chlorinated hydrocarbons of major importance because of their high levels are considered as DDE, DDT, TDE and PCB-like residues. Dieldrin and other chlorinated hydrocarbon residues not evaluated in this study remain a problem for future research.

RESULTS AND DISCUSSION

General observations concerning wild adults

The alewife most likely represented the dominant food source of Lake Michigan herring gulls during the general period in which this study was conducted. In 1965, this species was estimated to comprise approximately 74% of the total weight of Lake Michigan fish in exploratory trawl catches (Bureau of Commercial Fisheries 1966, hereafter called BCF). Ludwig (1966) has shown its importance as a food of herring gulls during the breeding season, but believes that insects were formerly more important in the birds' diet. He found that alewives comprised 83% of occurrence, smelt (Osmerus mordax) 10% and yellow perch (Perca flavescens) 3% of the diets of Lake Michigan and Lake Huron herring gulls, to attest to the importance of fish in the general diet in spring. The alewife has been abundant in Lake Michigan since the mid-1950's, is present in large numbers in all parts of the lake, and was believed to be still increasing in 1966 (BCF 1966).

During the early winter of 1966-67, large numbers of herring gulls fed at various city dumps for about one-fourth of the year. By February no gulls could be found in any of the five dumps we visited, although large amounts of garbage were still available. Our hunting pressure did not seem to affect the gulls' use of dumps, as local caretakers reported large numbers soon following our efforts. Fish remains discarded there by fish processors even then seemed important in the birds' diet.

Later in the winter, we found herring gulls congregating about winter-fishing operations, in active harbors, along the ice-sheet edges 150 m or more offshore, and 1/2 to 4 km offshore over open water. At

this time, gulls were feeding on fishing debris and unwanted species (mostly alewives) discarded by fishermen and turned up in the backwashes of fishing vessels. Gulls also appeared to be feeding on materials not associated with any human activities.

Our small samples in stomach and esophageal analysis (Table 3) were evaluated on a qualitative basis only, but the data indicated general food-habits of the wild herring gulls we studied in 1966 and 1967. Fish included chubs, smelt, yellow perch and possibly other fish species in addition to the dominant alewife. Plant materials included Polygonum seeds, Ulmus leaves, Thuja tips, grass blades and unidentifiable stems and leaves (tree and lawn trimmings?), most of which was probably picked up incidentally to other food items. Actual identifiable garbage included meat trimmings, potato peels and pieces, noodles, lettuce, eggshells, and associated items such as toothpicks and miscellaneous wrappers. Invertebrate materials included remains of Coleoptera, gastropods, crustaceans, and unidentifiable insect parts. Items classified as "miscellaneous" included feathers and gravel. All items but fish and garbage represented minor food items. It is apparent that Lake Michigan herring gulls are predominantly fish-eaters.

The most important potential factor regarding residue levels in food which might have "diluted" the residue levels of wild birds during the winter months was garbage. Miscellaneous, random collections from esophagi did not bear this out, however, as the few samples suggested that residues in "garbage" were at least comparable or higher than those in alewives. Pork fat, representing meat trimmings, a common form of garbage, taken from a single bird in August 1966 averaged 3.85 ppm (wet-weight) of DDE, 0.28 ppm of apparent PCB, with DDT and TDE

TABLE 3. Qualitative list of food items of Herring Gulls collected on western Lake Michigan shores as observed in stomachs and esophagi from 1966 to 1967*

Quantity	Date of observation						
	31 May '66	3 Aug '66	4 Oct '66	9 Dec '66	11 Feb '67	27 Apr '67	Total
No. birds shot in dumps	0	0	6	6	0	0	12
No. birds shot near water	10	10	4	2	4	10	40
No. of item occurrences	29	22	20	15	10	23	119
Food-items (% occurance)							
Alewives	45	59	30	20	40	35	40
Other fish**	21	18	20	27	60	30	26
Plant material	10	9	5	13	0	13	9
Garbage	0	5	25	33	0	4	10
Invertebrates	10	5	5	0	0	4	5
Misc. items	14	5	15	7	0	13	10

* This representation in no way gives biomass. Fish (mostly alewives) predominated in the diet. Each identifiable individual item or animal was counted as one occurrence, i.e. a mass of alewife remains was counted as one occurrence.

** Includes possibly alewives and all other species.

undetected. A pool of esophageal contents from gulls shot on 4 October 1966 averaged 3.94, none detected and 12.7 (Fig. 3b). This pool was composed of fish remains along with mixed garbage and much unidentifiable material. Plastic wrappers were commonly found in many of the gull stomachs.

Chubs (Leucichthys sp.) on which gulls were found feeding (discarded by fishermen) contained 4.31, 1.26 and 1.53 ppm (wet-weight) of the residues DDE, DDT + TDE and apparent PCB, respectively. Partly digested alewives taken from esophagi and stomachs of herring gulls shot near their breeding colonies on 3 August 1966 averaged 1.25 ppm DDE, 0.18 ppm DDT + TDE and 0.26 "ppm" apparent PCB. These values are the lowest we found for any alewives and suggest that samples taken directly from the alimentary tracts may somewhat underestimate the actual residues present. Alewives (2 pools of 25 fish each) picked up fresh near the breeding colonies on 23 June 1967 averaged 2.44, 0.97 and 1.39 of the same chlorinated hydrocarbons.

About all that we can conclude from the above observations is that in these Wisconsin dumps, chlorinated hydrocarbon residues were present that were as high or higher than those found in natural food; DDT and TDE residues were not detectable in the few garbage representatives not definitely associated with discarded fish.

In early May, just prior to intensive nesting and breeding activity, flocks of 25 to 300 herring gulls could be found loafing on alfalfa and stubble fields near the shore. They were eating small insects at this time, but most activity appeared to be associated with reproductive behavior rather than feeding. Coleoptera taken by nesting gulls in this region ran 0.5 ppm DDE (wet-weight) in 1964 (Hickey et al. 1966).

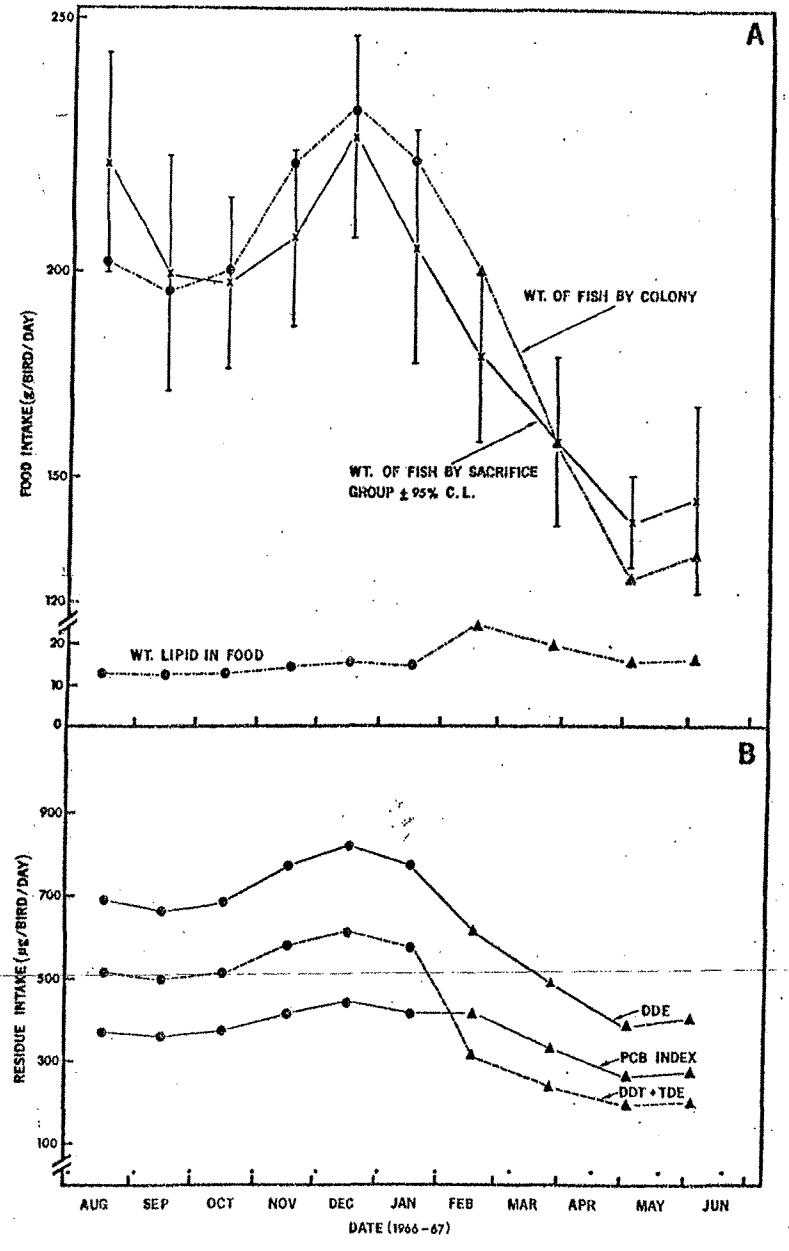
Juvenile food consumption and general observations

We found that the weight of alewives, their corresponding water and lipid contents and their chlorinated hydrocarbon residues varied between late spring and early summer (Table 1). Since p,p'-DDT is commonly converted to p,p'-TDE in frozen specimens under anaerobic conditions (Jefferies & Walker 1966), we felt these had to be considered together in data analysis. The 1966 levels of DDT-complex (DDE + TDE + DDT) residues in alewives from our August batch 2 (Table 1) were only slightly higher (on a ppm, wet-weight basis) than those reported by Reinert (1969) for our general study area; however, May batch 1 alewives were higher (by about 1 ppm) than any alewives he reported for Lake Michigan. Reinert (1970) reported a general DDT-complex of Lake Michigan alewives in 1967-68 as 3.89 ppm (96 analyses), a value which we believe to be closely comparable to the general levels we found. On a 100% lipid basis, the residues reported by Reinert were 37.6 ppm, compared to 38.1 ppm in batch 2. The higher levels in batch 1 on a lipid basis (93.1 ppm) suggest a seasonal variation in alewife residues not strictly related to fat reservoirs (Table 1).

Actual weight of food consumed per captive herring gull per day peaked in December and dropped to a low in early May (Fig. 3a). Food consumption was probably again on the increase after that low. The April-May low in food consumption coincides with the normal breeding season of Green Bay herring gulls, although these juveniles were not comparable in gonadal development to adults. The general period of peak egg-laying during the springs of 1966 to 1968 was late-April to mid-May.

We found that juvenile gonads were discernable by September

FIG. 3. Seasonal variation in the amount of food and associated fat and residue components ingested by penned, juvenile herring gulls. Since periods between samplings were not equal, points are placed at midpoints for each period and are expressed as units/bird/day. Sampling dates are shown with a small dot near the lower axis. Closed circles represent batch 1 alewives, and triangles represent batch 2.



following fledging, but not readily so until December. Juvenile gonads were at their maximum, however, by mid-June 1967, but still not then comparable in size to adult gonads in their most regressed stage during the winter (juvenile ♀ = 5 by 8 mm, juvenile ♂ = 1 by 3 mm; regressed adult ♀ = 6 by 10 mm, regressed adult ♂ = 3 by 5 mm). Juveniles were molting primaries and contour feathers in June 1967 and beginning to show typical subadult plumage. One juvenile, however, a dark bird, was molting into new feathers as dark or darker than its original plumage.

We found that our captive herring gulls rarely failed to eat during each day, except during short periods of extreme heat or cold. Average weight of food consumed by the experimental colony and the groups we sacrificed were comparable (95% C. L.) in all instances but one (Fig. 3a), which we consider as a 1 in 20 sampling mischance. A noticeable increase in amount of lipid consumed occurred in February and March 1967, although actual weight of fish consumed was dropping (Fig. 3a), solely as a function of the doubling of percent lipid in batch 2 alewives.

It can be seen that resultant residue exposure solely from the food viewpoint in our experimental group (Fig. 3b) was a possible function of at least three different variables: (1) variations in amount of food consumed throughout the year, (2) variations in lipid content of food and thus in the potential residue reservoir or carrier, or both, and (3) variations in residue content of that food possibly related to different seasonal exposures faced by alewives or variable pesticide kinetics in alewives at different times of the year. Robinson et al. (1967) have demonstrated distinct seasonal variation in two species of fish from the east-British coast to further support this final conclusion.

Annual weight and fat changes

The affinity of most chlorinated hydrocarbon residues for fatty tissues leads to inquiry concerning variations in lipid weight (volume) as possibly related to total body burden. Herman et al. (1969) showed that TDE concentrations in various tissues of western grebes (Aechmophorus occidentalis) were related to their fat content, but no information was available on total body burden. The consideration of adipose tissue in the compartmental model of pharmacokinetics as generally applied to chlorinated hydrocarbons (see Mrak et al. 1969: 271-273 for a review) dictates the importance of understanding seasonal changes in the lipid deposition of birds.

Sexual dimorphism in size is well known in larids but is not related to differential niche utilization or food-habits between the sexes (Ingolfsson 1969). Fully aware that males are largest, we chose to combine the sexes for our data analysis here, so that values should be considered as "average adult" rather than representative of any one sex. Sex ratios in our sample were not significantly different from a 50:50 ratio as determined by Chi^2 ($P<0.1$).

Weight and lipid deposition in both adults and juveniles followed a similar pattern over the year after early weight gains by juveniles (Table 4). Lipid deposition in juveniles, however, was greater in all cases, even though fat-free carcass weights were consistently lower than those of adults. Adult weights varied less than those of juveniles (Fig. 4; CV, adults = 4%; CV, juveniles = 13%), with a small adult weight-increase associated with molt in early August 1966, and a large increase in early 1967 due to increased fat deposition (Table 5).

TABLE 4. Changes in body characteristics of adult and juvenile Herring Gulls from 1966 to 1967*

		Adults (mean ± SE)					Juveniles (mean)**				
General Period	No.	Total Body Wt.	Wt. Lipids in Carcass***	Wt. Fat-free Carcass	% H_2O in Carcass	Wt. 1 Breast Muscle	Total Body Wt.	Wt. Lipids in Carcass***	Wt. Fat-free Carcass	% H_2O in Carcass	Wt. 1 Breast Muscle
Jun '66	10	1082 ± 31	53 ± 12	571 ± 19	65 ± 1	70 ± 3	-	-	-	-	-
Aug	10	1175 ± 54	44 ± 6	594 ± 27	65 ± 1	71 ± 3	937	46	492	66	48
Sep	-	-	-	-	-	-	974	121	492	52	60
Oct	10	1087 ± 43	42 ± 7	559 ± 23	65 ± 1	75 ± 3	1157	238	580	42	64
Nov	-	-	-	-	-	-	1141	270	517	36	66
Dec '66	8	1149 ± 50	104 ± 16	573 ± 22	55 ± 2	74 ± 4	1180	239	516	39	70
Jan '67	-	-	-	-	-	-	1334	337	535	31	76
Feb	2‡	1200 ± 45	180 ± 14	553 ± 25	48 ± 1	67 ± 4	1328	314	535	30	73
Mar	-	-	-	-	-	-	1269	267	532	35	71
Apr	10	1123 ± 48	62 ± 7	588 ± 24	62 ± 1	77 ± 3	1017	107	496	53	70
May	-	-	-	-	-	-	1054	102	537	55	68
Jun '67	-	-	-	-	-	-	1002	80	497	58	63

TABLE 4 continued.

TABLE 4 continued.

* All weights are expressed in grams.

** These are pool means of 5 birds each, except the June 1967 sample on which the following standard errors and coefficients of variability were calculated: body wt. = 55 g, 11%; wt. lipids = 4 g, 13%; wt. carcass = 70 g, 14%; percent water = 1%, 4%; breast muscle weights probably reflected some variation due to lipid storage.

*** These values probably represent the major portion of stored body lipids, since most of the hard parts removed contained little fat.

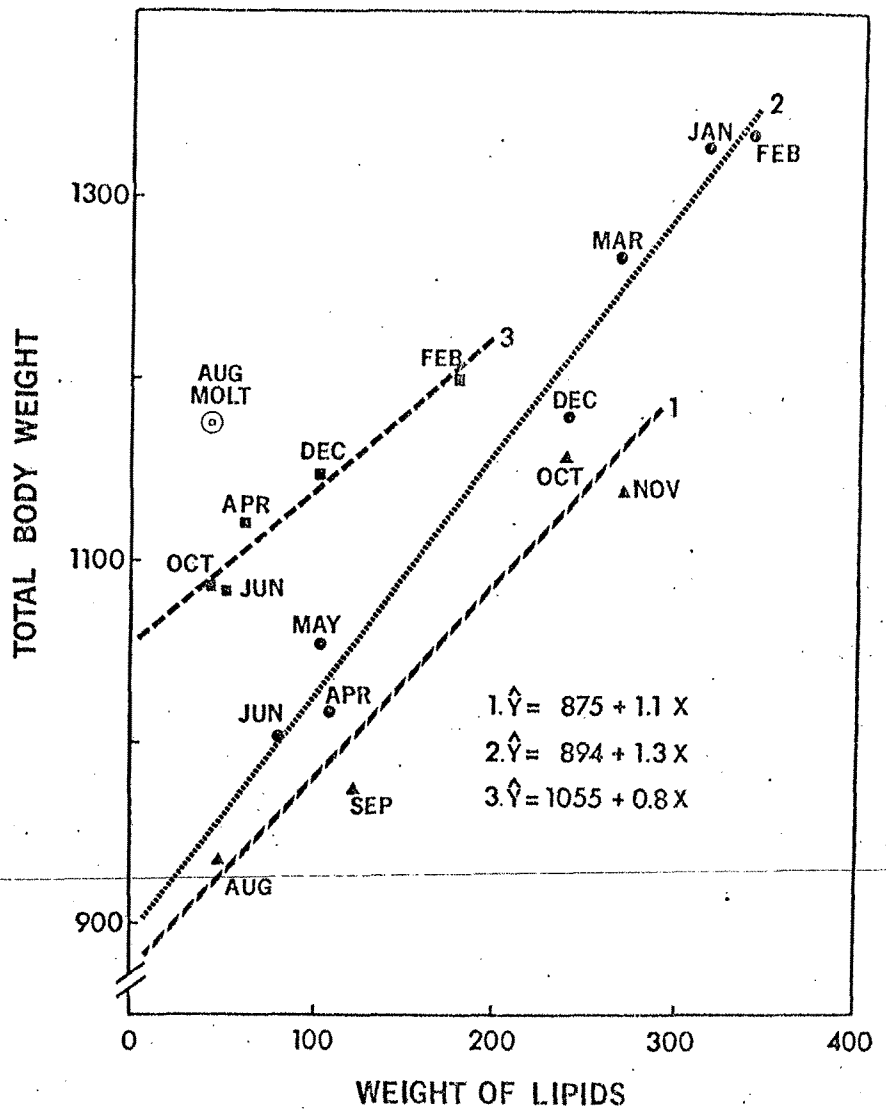
‡ Both of these birds were females.

Slightly smaller fat-free carcass weights in all juveniles throughout the experimental period suggested that these birds had completed most, but not all, growth in their first year. Breast-muscle weights did not vary significantly over the year in either age class after initial increases in caged juveniles, and they were only slightly smaller in caged juveniles (Table 4). Comparisons between fat weight and total body weight fell into three categories (Fig. 4). Postfledging juveniles stored fat reserves heavily during their first 4 months. During the remainder of the year, the caged juveniles continued to store fat more heavily than adults.

The increased lipid stores in juveniles may have been in part a function of their being captive, or a function of their immaturity. Adults would be expected to metabolize greater amounts of lipids in the wild where food would not be so constantly available. Greater fat deposition in first-year birds may be a general adaptation to their first year of necessarily independent life (see Tinbergen 1960:25-38). The two wild-collected juveniles in February 1967, weighed as much as caged juveniles (1323 g vs. 1328 g) but stored slightly less fat (222 g vs. 314 g). In any case, they were more like caged juveniles than adults, to support the hypothesis of increased fat deposition in young, wild birds. Increased lipid deposition in juveniles, where we had data on food intake, was at least in part related to the amount of food consumed (Fig. 3, Fig. 6).

Changes in body weight in both wild adults and caged juveniles seemed most closely related to the amounts of fat deposited, except in wild adults in August, the period when they were molting heavily (Fig.

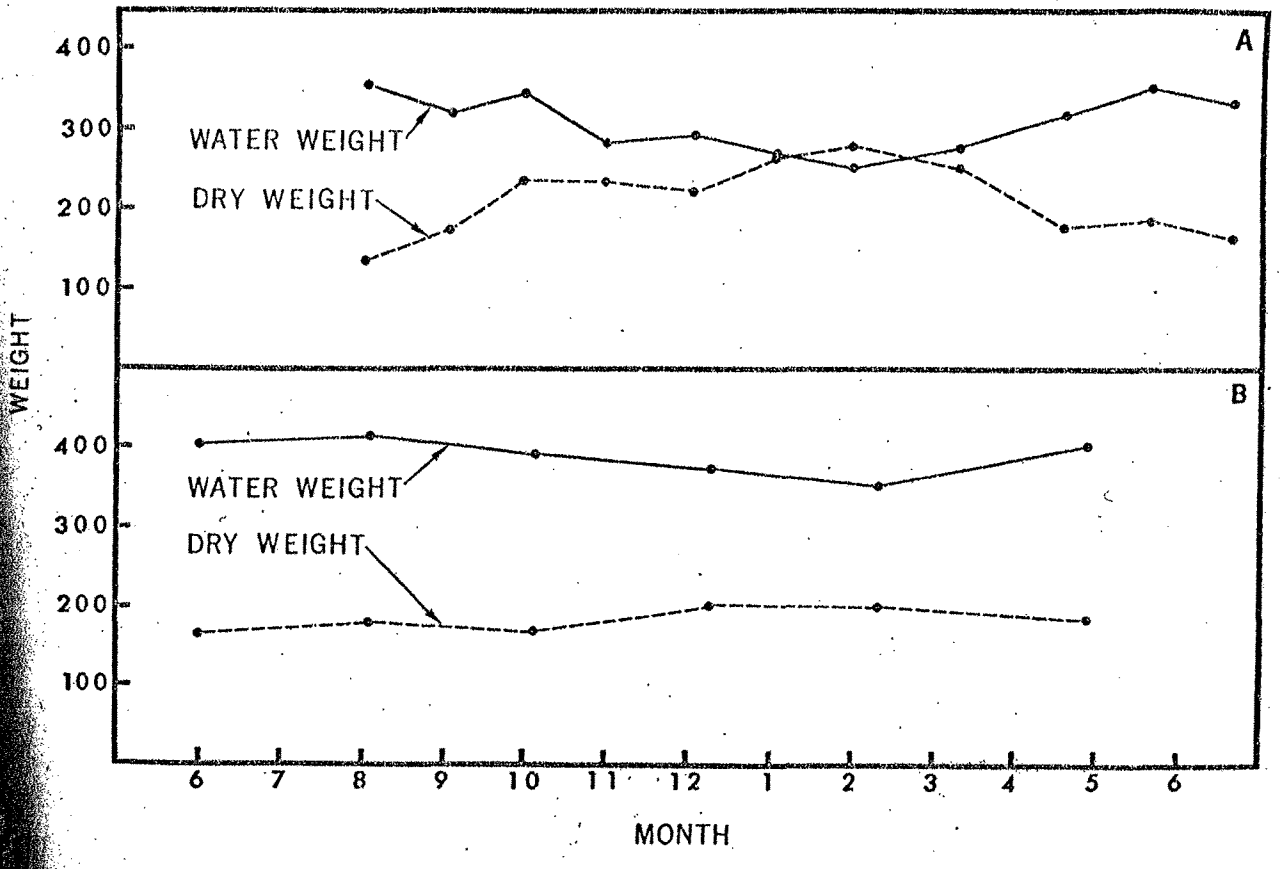
FIG. 4. Relationships between weight of deposited lipids and total body weight in different-aged herring gulls. Line 1 represents post-fledging juveniles (all caged except the August sample), $r = 0.969$, $P<0.05$. Line 2 represents caged juveniles after six months of age, $r = 0.989$, $P < 0.01$. Line 3 represents wild-shot adults, $r = 0.963$, $P<0.01$. The open circle represents molting adults and was not used in the calculations.



4). This molt correlates with the general postnuptial molt described by Dwight (1925:93-96) for large larids in general. By the time we started collecting juveniles, they had already completed major feather growth. King et al. (1965) showed a decrease in fat-free body weights correlated with postnuptial molt in white-crowned sparrows (Zonotrichia leucophrys). The fat-free body weights of August herring gulls increased only slightly. We therefore conclude that the total weight increase was associated with the parts we removed, probably the wings and feathers. Perhaps the increased fat-free carcass weights in adults (Table 5) reflect increased synthesis of feather proteins and increased water, etc. in the parts we removed.

Nonfat dry weight of adult carcasses was relatively constant throughout the year, although slight increases appear to have occurred during the winter (Fig. 5a). Child (1969) has described the year-round constancy of water to nonfat dry weight in Swainson's thrushes (Hylocichla ustulata), and similar relationships were described by Child and Marshall (1970). This relationship, however, was even more distorted in our caged juveniles (Fig. 5b), and cannot be explained on the basis of sampling error or unbalanced sex ratios. Two hypotheses are offered: (1) increased protein synthesis occurred during the winter months in juveniles, and (2) increased glycogen storage or synthesis occurred during the winter. Hanson (1961), studying energy reserves in Canada geese (Branta canadensis interior), showed that glycogen reserves were utilized first for energy, but he suggested than an interrelationship existed between carbohydrate, fat and protein metabolism. It may be that increased glycogen synthesis is needed to maintain the herring gull in winter on Lake Michigan. Maximum fat and minimum "water storage"

FIG. 5. Variation in nonfat dry weight and weight of water in juvenile (A) and adult (B) herring gulls over a period of one year.



occurred in both age classes during the coldest period of the year (January-February). By April, fat levels were generally comparable with those of the previous May.

Young herring gulls are known to be much more migratory—rather, they show a greater tendency for dispersal—than adults (Gross 1940, Smith 1959). The idea of lipid deposits as a "fuel" for migratory flights has been proposed in such studies as Odum & Connell (1956), Raveling & LeFebvre (1967), and others. Weise (1963) suggested that extensive vernal fat deposition in several species of overland-migrating passerines was primarily an adaptation to unfavorable weather conditions. Baldwin & Kendeigh (1938), studying gross weights in 24 species of birds, showed a general inverse relationship between weight and temperature; and, differences in "weight-temperature" curves between different species were suggested as being related to migratory status and distribution. The potential importance of stored energy and physical condition (both tied in part to lipid reserves) to winter survival in such sedentary species as house sparrows (Passer domesticus) and ring-necked pheasants (Phasianus colchicus) has been demonstrated (Davis 1955, Kabat et al. 1956). Lipid reserves might function not only as potential energy reserves but also as additional insulation to protect against heat loss. Brenner (1967) suggested that the adaptive value of reserve energy supplies in red-winged blackbirds (Agelaius phoeniceus) was not as importantly tied with migration per se as it was with reproduction and inclement-weather needs. The general role of internal rhythm in regulating physiological changes in birds, including lipid changes, in relation to migration and breeding is reviewed by Marshall (1961:307-339). In general, the degree and condition of

migratory state (viz. the distance, route and climatic circumstances surrounding movements and distribution) as related to the internal rhythm, seem to dictate the chronology, degree and adaptive function of fat deposition.

In herring gulls from Lake Michigan, fat deposition seems to have a major adaptive function in conditioning the birds to environmental changes associated with winter conditions. Possible roles of large amounts of fat at that time may relate to both insulation and labile energy stores. In juvenile herring gulls, even greater amounts of stored fat (other than those we observed as possibly related to captivity) might serve the additional function of having adapted the birds to an independent life in competition with more experienced adults and to a more nomadic habit than adults.

Relationships of sampled "tissues"

We feel that the most reliable index to seasonal changes in body burden is mg/kg (ppm) in whole carcass homogenates because these values comparatively represent the body burdens of different-sized birds. It also seems most suitable in calculating the total micrograms present (an absolute measurement of body burden). Dindal (1970) has shown that fat samples (ppm wet-weight) vary considerably from site to site on the carcasses of mallards (Anas platyrhynchos) and lesser scaup (Aythya affinis). He warned against the use of such in extrapolating to body burden. We found that micrograms in carcass as based on the small fat biopsies from individual, wild adults failed to represent total carcass micrograms as calculated from mg/kg values; but, in juveniles where fat was more easily obtained and where samples were pooled and large, the

relationship was more satisfactory (Table 5). Breast-muscle extractions (whole breasts) more closely represented total-carcass homogenates in both relative lipid content and ppm lipid-basis, thus amount of chlorinated hydrocarbons present (Table 5). The carcass (X) and breast (Y) lipids were related as expressed by the regression equation, $Y = 2.86 + 0.13 X$, with both juveniles and adults combined. Neither the slopes nor the intercepts of adult and juvenile regressions were significantly different from one another (non-overlap of 95% Confidence Limits as described in Simpson et al. 1960:224-229). The intercepts were significantly different from zero and suggested that lipid levels below 2.9 minus 1.3 percent in breast (lower C.L.) were not associated with seasonal fat storage but rather other physiological functions. Percent lipid in carcasses was likely dominated quantitatively by seasonal fat changes and most representative of that value. "Fat" biopsies from our adult herring gulls varied seasonally in extractable-lipid content as follows (means $\pm$ 95% C.L.'s in sequence of collection): $58\pm10\%$, $58\pm13\%$, $50\pm18\%$, $82\pm4\%$, $81\pm11\%$, $79\pm5\%$. Juveniles varied in a similar pattern from 51 to 99 percent but were more consistent at the higher percentages after October 1966. The seasonal differences in the above-described lipid contents of "fat" more likely represented variations associated with differences in lipid storage, resulting in variations in the relative amounts of other tissues such as water and possibly connective tissue.

The data suggest that muscle biopsies might be more satisfactory in monitoring wild birds where whole carcasses are not available or in remote field situations where whole specimens cannot be saved.

Levels of DDE and apparent PCB in eggs represented adult-body

TABLE 5. Comparisons between measurements of residues by different methods and in different tissues

Variables		r, adults	r, juveniles
Independent	Dependent	(n=6 periods)	(n=11 periods)
% lipids, carcass	% lipids, breast	0.94**	0.90**
MICROGRAMS DDE IN STRIPPED CARCASS BASED ON			
mg/kg (ppm) in carcass	fat biopsy and wt. extracted fat	-0.10	0.59‡
MICROGRAMS APPARENT PCB IN STRIPPED CARCASS BASED ON			
mg/kg (ppm) in carcass	fat biopsy and wt. extracted fat	-0.22	0.77**
PPM DDE, LIPID-BASIS IN			
stripped carcass	breast muscle	0.93**	0.99**
PPM APPARENT PCB, LIPID-BASIS IN			
stripped carcass	breast muscle	0.88**	0.87**

‡ approaching 95% significance.

* significant at 95% level.

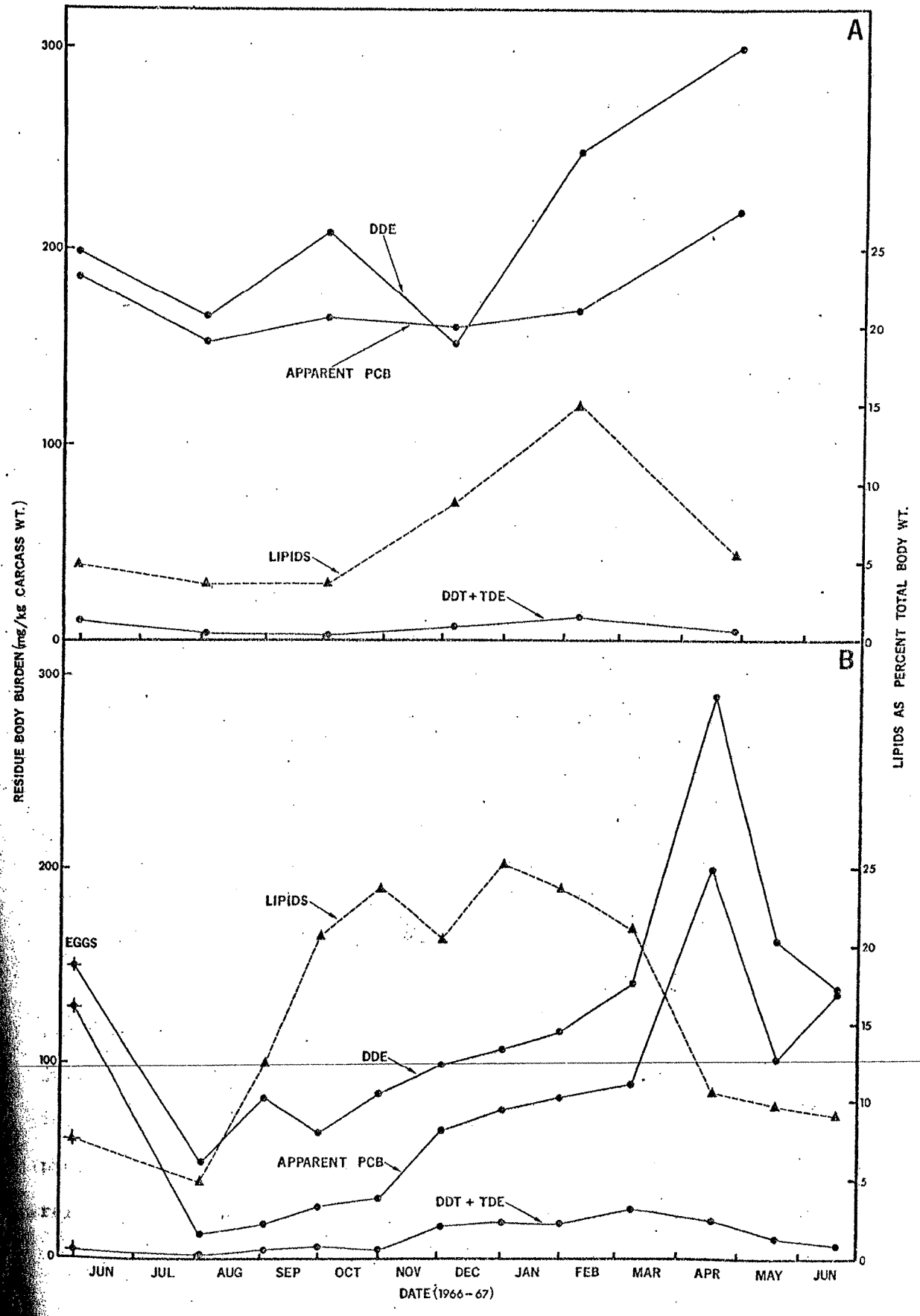
** significant at 99% level.

burdens (mg/kg) multiplied by an average factor of 0.75. When comparisons were made on a lipid-basis, the factor increased to 0.95. DDT + TDE was present in small amounts (6% of DDE + TDE + DDT in adults and 2% in eggs) and the factors varied from 0.4 to 0.5. We have generally found very low levels of DDT + TDE (relative to DDE) in herring gull eggs from Lake Michigan since our 1966 sample. Enderson & Berger (1970) reported a positive correlation between ppm lipid-basis dieldrin in eggs and fat of prairie falcons (Falco mexicanus), but the factors calculated by us for high (60-100 ppm) and low (25 ppm) levels were only 0.18 to 0.32. The correlation between levels (ppm wet-weight) in breast muscle and levels in eggs from oviducts of western grebes reported by Herman et al. (1969), though no conversion factor was given, further support the relationship between adult female residues and residues in her eggs. We regard egg residues as an index to female condition, thus an indirect, but valid measure. Residue levels in egg contents representing field data have been related to eggshell changes in several species (Hickey & Anderson 1968, Anderson et al. 1969, Fyfe et al. 1969, and others).

Seasonal residue changes

The overall picture of seasonal residue changes in adult and juvenile herring gulls is represented in Fig. 6. Breast and carcass residues followed similar patterns, as expected; thus, only carcass-based residues are expressed here. Temporal variation in pesticide residues has been demonstrated by Robinson et al. (1967) with dieldrin in shags (Phalacrocorax aristotelis), by Herman et al. (1969) with DDT/TDE-derived compounds in western grebes, by W. L. Anderson et al.

FIG. 6. Seasonal variations in the body burdens of chlorinated hydrocarbons in adult (A) and juvenile (B) herring gulls from 1966 to 1967.



(1970) with DDE, dieldrin and heptachlor epoxide (1,4,5,6,7,8,8= heptachloro-2,3-epoxy-3a,4,7,7a-tetrahydro-4,7-methoniondan) in ring= necked pheasants, and others. Various explanations have been given for such changes. The decrease in relative "body burden" (mg/kg) from eggs to fledglings (Fig. 6B) is similar to that described for shags by Robinson et al. (1967). It is presumably a "dilution" in relative body burden by growth. Total micrograms of DDE and apparent PCB, respectively, in eggs versus fledglings, increased or decreased depending on the residue: from 1.5×10^4 to 2.3×10^4 and from 1.2×10^4 to 5.9×10^3. All residues in adults (Fig. 6A) seemed to follow a cyclic pattern, varying somewhat in relation to the fat cycle. DDE ran opposite the fat cycle in December 1966 and between February-May. The only explanation for the December decrease in DDE that we can offer is the possible dilution by human garbage at that time. It did not occur with the other residues, nor did it occur in juveniles being fed alewives at the same time (Fig. 6B). Apparent PCB in adults seemed stable at around 160 mg/kg (the average of the four middle points and considered here as "equilibrium"), except in May and June, the breeding season. Our best estimate of a theoretical "equilibrium" for DDE was considered as the mean of months 2 through 4, 175 mg/kg. These means are estimated and theoretical in equilibrium concept, and they are proposed here for discussion purposes. They seem to represent one phase of two in the adult residue-picture and one in three for caged juveniles. DDT + TDE in both adults and juveniles was closely related in direction of change to the lipid cycle (Fig. 6). The three apparent phases in juveniles for DDE and apparent PCB are (1) dilution of relative amounts from egg to fledging by probable growth, then general

stabilization of weight, (2) post fledging buildups to "equilibrium" levels until the following early spring and (3) sudden increases in body burden associated with rapid decreases in lipid reserves, followed by a return to "equilibrium." The theoretical "equilibrium" levels in phase 2 for juveniles were estimated by eye for both DDE and apparent PCB (we assumed the curves would follow an asymptotic form such as that described by Laug et al. 1950), and they are given in Table 6. Phase 3 implies that ppm lipid-basis in fat samples had to increase, since body burden (mg/kg) increased when lipid reserves decreased. We found that this supposition held in juveniles where fat biopsies were generally satisfactory, but it could not be observed in adults. The values (ppm lipid-basis in fat biopsies) for juveniles in sequence were as follows: DDE = 442, 306, 189, 252, 231, 192, 244, 298, 968, 1927, 915; Apparent PCB = 146, 67, 82, 94, 203, 229, 223, 219, 507, 776, 629. Phase 3 residues represented the maximum levels attained in both juveniles and adults, when the two age classes were closely comparable. Juvenile levels were 290 mg/kg DDE, 19 mg/kg DDT + TDE. and 200 mg/kg apparent PCB. This compared to wild adults as follows: 300 mg/kg DDE, 4 mg/kg DDT + TDE, and 219 mg/kg apparent PCB.

In general, it seems safe to conclude that caged juveniles fed Lake Michigan fish assumed a residue pattern similar to adults in their first year, acquiring phases 2 and 3, and then probably continuing as such. Residue buildups of DDE in juveniles similar to the residue levels in wild, spring adults occurred in the same time periods on a fish diet of generally 3 ppm DDE, 2 ppm DDT + TDE and 2 ppm apparent PCB (Table 1). The contribution of dietary DDT or TDE, or both (see Abou-Donia & Menzel 1968, Ecobichon & Saschenbrecker 1968 and Bailey

et al. 1969a, b) as well as dietary DDE to total body burdens of DDE in herring gulls seems clear, and the rapid and extraordinary accumulation of DDE compared to DDT + TDE was most likely related to both (Table 6). Carcass residues on a ppm lipid-basis, however, were much lower in juveniles which had more fat: 1305 ppm compared to 2558 ppm and 10.5% (whole-bird basis) compared to 5.4% lipid in adults. The smaller relative amounts of fat in adults at this time were presumably related to additional stresses associated with breeding; nonetheless, resulting DDE body burdens were about the same. It may be, however, that the larger concentrations of residues in adults may be of more physiological importance.

Based on the assumption that peak tissue storages of the chlorinated hydrocarbons discussed here behave as DDT and dieldrin in phase 2 of the annual cycle, that is, that they are directly related by some factor to daily dose (reviewed by Hayes 1959:58-70 and Mrak et al. 1969:263-265), poor adult-juvenile comparisons of theoretical "equilibrium" levels for apparent PCB and DDT + TDE (Fig. 6) suggest that additional food sources with less DDT + TDE and more apparent PCB than found in our alewives partly contributed to the adult residues.

GENERAL DISCUSSION AND DATA CONSOLIDATION

The concept of "equilibrium" levels (see Laug et al. 1950, L. F. Stickel et al. 1966, Robinson 1967, Robinson and Roberts 1968, Mrak et al. 1969 and others) seems to apply only in part to the annual residue cycle in herring gulls, the initial buildups of phase 2. Unfortunately, as we did not measure liver residues and weight (volume) changes, we cannot apply the compartmental model to our juvenile data generally as

TABLE 6. Change in relative proportions of DDE, DDT+TDE and apparent PCB from diet to body burden of caged, juvenile herring gulls in the "equilibrium phase" (Phase 2) of residue accumulation

Variable (unit)	DDE	DDT+TDE	Total DDT-complex	Apparent PCB	Residue Total
Dietary (µg/day)**	686	481	1167	389	1556
"Equilibrium" (mg/kg)	170	19	189	120	309
Proportion of total residues					
in diet	.44	.31	.75	.25	1.00
in birds	.55	.06	.61	.39	1.00
Percent change of proportion	+25%	-81%	-19%	+56%	-

* "DDT-complex" residues were considered here as DDE+TDE+DDT. The ratio of DDE/DDT+TDE was 1.43 in the fish diet and 8.95 in juvenile herring gulls; DDE/PCB = 1.76 and 1.42.

** These values are the means of months 1 through 8 on diet.

described by Mrak et al (1969) and Robinson et al. (1969). Our initial calculations concerning the total, yearly dynamics of chlorinated hydrocarbon residues were based on monthly changes, since so many potentially influential variables were in a constant state of flux (Table 7). Of course, percent of total intake lost exceeded 100% when the gulls were in the "return to equilibrium" portion (phase 3) of the annual cycle (Table 7, periods 9 and 10, between 8 and 9, and 9 and 10) when stored residues were presumably being lost as well. We suspect that greater turnover rates in the central compartment were most important in these changes.

During phase 2 (periods 1 to 7, months 1 to 8) we applied drug absorption formulae (Nelson 1961) as previously applied to heptachlor in woodcocks (Philohela minor) by W. H. Stickel et al. (1965a). The basic assumption of this general model is that each daily dose yields a given concentration, but that the loss from the animal is proportional to the amount present (also Robinson 1967). Based on these calculations (Table 8), nearly all of the DDT-complex residues were taken into the body. Residues of p,p'-DDE most likely represented, as already suggested (Table 6), partial conversion from other DDT-related residues and partial buildup of dietary DDE. The large gain rates calculated for apparent PCB (Table 8) seem explainable on one of two bases: (1) the basic assumption that loss rate is constantly proportional to amount present does not hold and these residues tend to be more accumulative than would be predictable by normally used models, or (2) our estimates of apparent PCB's were either too low for fish or too high for birds. The suggested increase of a higher number PCB in adults (Fig. 2e) points to both possibilities, as higher number (higher chlorine content) PCB's

TABLE 7. Monthly residue dynamics in captive, juvenile herring gulls fed Lake Michigan alewives for a period of 322 days

Residue Variable	Period ( ) 1	2	3	4	5	6	7	8	9	10
No. days in period	31	28	32	31	31	30	36	40	32	31
p,p'-DDE										
µg in body at start*	2.33	4.49	4.76	5.95	6.73	8.46	8.98	10.24	15.34	9.29**
µg intake*	2.14	1.86	2.18	2.39	2.53	2.32	2.20	1.92	1.22	1.24
µg gained or lost/day*	0.07	0.01	0.04	0.03	0.06	0.02	0.04	0.13	0.19	0.07
% previous µg in body	93	6	25	13	26	6	14	50	-39	-24
p,p'-DDT + p,p'-TDE										
µg in body at start*	0.05	0.19	0.42	0.31	1.08	1.47	1.35	1.77	0.99	0.56***
µg intake*	1.60	1.39	1.63	1.78	1.89	1.73	1.13	0.98	0.62	0.63
µg gained or lost/day*	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01
% previous µg in body	280	121	-26	248	36	-8	31	-44	-43	-34
DDT-complex residues										
µg gained or lost/day*	0.07	0.02	0.03	0.05	0.07	0.01	0.05	0.11	0.20	0.07
% previous µg in body	97	11	21	25	27	2	19	36	-40	-24

Table 7 continued.

Table 7 continued.

Residue Variable	Period 1	2	3	4	5	6	7	8	9	10
Apparent PCB residues										
µg in body at start*	0.59	0.96	1.94	2.16	4.51	6.00	6.28	6.43	10.59	5.80‡
µg intake*	1.15	1.00	1.18	1.29	1.37	1.25	1.49	1.30	0.83	0.84
µg gained or lost/day*	0.01	0.04	0.01	0.08	0.05	0.01	0.01	0.10	0.15	0.04
% previous µg in body	63	102	11	109	33	5	2	65	-45	20

* Conversion factor = 10^4.

** µg in body at end of period = 7.08×10^4.

*** µg in body at end of period = 0.37×10^4.

‡ µg in body at end of period = 6.96×10^4.

TABLE 8. Residue dynamics for the gain period in juvenile herring gulls fed Lake Michigan alewives for a period of 219 days

Residue	Loss rate (%/day)*	Daily dose absorbed (μg)	Mean daily intake (μg)	Percent of daily dose absorbed
p,p'-DDE	0.67	916	686	134%
p,p'-DDT + p,p'-TDE	1.64	320	481	67%
DDT-complex residues	0.74	1155	1167	99%
Apparent PCB	1.09	842	389	216%

* Calculated as described by W. H. Stickel et al. (1965a).

are known to be more accumulative than the lower ones in food-chains (Jensen et al. 1969), and thus overall PCB loss rates would be expected to decrease proportionately as PCB levels increased in the body, resulting in disproportionately high estimated percentages of daily dose absorbed. Further research is needed concerning the physiological behavior of PCB's in avian tissues. The overall percentages (means of monthly rates) of total doses retained (overall means from Table 7) were: DDE = 50%, DDT + TDE = 16%, DDT-complex = 46%, and apparent PCB = 64%. The difference between DDT-complex and apparent PCB is presumably related to differences in accumulative behaviors of these residues.

W. H. Stickel et al. (1965a) reported 16-20% absorption (daily dose) of heptachlor in woodcocks fed contaminated earthworms and calculated an instantaneous loss rate of 2.8% per day. W. H. Stickel et al. (1965b) reported a loss rate of 4.5% per day in woodcocks fed capsules of heptachlor. L. F. Stickel et al. (1966) reported loss rates of 0.2 to 0.4% for DDT in bald eagles, these values being most similar to those we observed for herring gulls.

The residue levels in alewives seem low in relation to the high amounts eventually accumulated in juvenile herring gull tissues but they are likely explainable on the basis of the high absorption and retention values observed for DDT-complex and apparent PCB residues (Tables 7 and 8). Perhaps alewives represented food which was nearly ideal for maximum absorption of lower food-web residues by herring gulls. It has been shown (Dindal 1970) that in lesser scaup and mallards, rates of residue absorption were uniform when the ducks were feeding on animal material; rates were sporadic when the ducks were

feeding on plant material. Dindal explains such delayed absorption or nonabsorption on the possible basis of adsorption of DDT molecules to nondigestable wax and cellulose materials of plants and possible phytosterol inhibition of normal intestinal absorption of cholesterol (citing Peterson 1951). These observations may partially explain one mechanism of many in the phenomenon of trophic concentration of chlorinated hydrocarbon residues in nature. Evidently, herring gulls have a high digestive efficiency, with few interferances such as might be expected in herbivorous species.

Perhaps a key observation in explaining the increased body burden associated with a decreased volume of part of the peripheral compartment in both adults and juveniles during phase 2 of the residue cycle is that of Dale et al. (1961). They observed that during starvation, increased concentrations of DDT-derived materials occurred in the fatty tissues of laboratory rats. Although augmented excretion of DDT-derived materials occurred at this time, residues were probably not lost at the same rate as fat, suggesting a change in residue metabolism at the time of lipid mobilization. Booth & Gillette (1962) demonstrated that increases in microsomal enzyme activity of rats administered certain androgens were more closely related to the anabolic activity than to the androgenic activity of the steroids studied. In mammals, several halogenated hydrocarbons are known to enhance metabolism of steroids and drugs by hepatic microsomal hydroxylase induction, although separate hydroxylase enzyme systems are probably involved for various reactions (Conney et al. 1967). Both DDE and DDT are known to cause large increases in liver weights of pigeons (Columba livia), to connect those

residues with hepatic function (Bailey et al. 1969a, 1969b), and Risebrough et al. (1968) have shown that PCB's are stronger enzyme inducers than even DDT. The liver is assumed to be the major site of lipid metabolism in birds (Couch & Saloma 1968), but the connection between lipid-metabolizing enzyme systems and those associated with halogenated hydrocarbons is purely speculative. The general relationship between steroid metabolism and chlorinated hydrocarbon metabolism has been established (see Conney 1967 and Kupfer 1967). It seems that several possible mechanisms are involved in the large body burden increases in spring herring gulls, probably relating chlorinated hydrocarbon metabolism to either lipid metabolism or steroid metabolism, or both. Steroid hormone levels are certainly highest during this period in adults as suggested by gonad sizes. Decreased activities of several foreign compounds are known to occur as a result of competitive metabolism between certain steroids and drugs by oxidative, liver microsomal enzymes (Tephly & Mannering 1964), with pregnant mammals and when certain steroid hormones are at high levels (Crawford & Rudolfsky 1966, Juchau & Fouts 1966). It is conceivable that during the period of increased gonadal activity in birds, the central compartment (of which liver is assumed a major component [Robinson et al. 1969]) becomes less efficient at chlorinated hydrocarbon metabolism and exchange, or in a sense "overloaded." The occurrence of increased body burdens in juveniles, however, which showed only very small gonadal increases, these having progressed slowly to that size, suggests that other factors were also involved. Changes in lipid metabolism in both age classes which was closely related in chronology to changes in residue dynamics suggest an intimate relationship between the two, as well. Any

changes in enzyme induction and liver function would likely change rate constants in the central compartment for various compounds as suggested by Robinson et al. (1969). This then would change the kinetic relationships between the compartments, in the case of herring gulls, resulting in an increase in retention of already highly absorbed daily doses of residues.

Crawford & Rudolfsky (1966) also suggested that human subjects would be more susceptible to drugs during such periods of greater retention and decreased metabolism. It follows, then, that herring gulls might be more sensitive to the toxic effects of the various chlorinated hydrocarbons at this time, as greater quantities of toxic materials would be expected to reach the central nervous system. Extensive data on brain residues are badly needed from dead birds found on the breeding colonies in spring. Hickey et al. (1966) concluded that 2 of 3 dead adults picked up on the breeding colonies, and tested in 1964, had died of pesticide poisoning. The role of chlorinated hydrocarbons in possibly increasing normal adult mortality on Lake Michigan herring gulls needs to be elucidated.

In summary, it can be seen that, under natural ecological conditions, the residue load in Lake Michigan herring gulls can conceivably be a function of various potential factors, these factors being related to both the ecology and physiology of the gulls. The variables we have discussed above might be generally summarized as follows:

(1) seasonal changes in food-habits or residue levels in a given food source, or both;

(2) possible seasonal changes in the amounts of food consumed, or

variations in daily intake;

(3) changes in the amount and function of stored body lipids, or changes in compartmental volumes, thus potential reservoir space for organochlorine residues;

(4) changes in the absorption, metabolism and excretion of chlorinated hydrocarbons as a result of changing lipid and steroid-hormone metabolism requirements placed on the liver (part of the central compartment);

(5) different physiological behaviors of the various chlorinated hydrocarbons present (as well as possibly additive or synergistic effects at varying concentrations not discussed) and

(6) possible changes in intestinal absorption of CH residues (although a potential factor, we found no suggestion of this).

Additional ecological factors which might be related to one or more of the variables above might be seasonal variation in chlorinated hydrocarbon usage or fallout, or even potential increases in input of past-used chlorinated hydrocarbons due to spring runoff each year. Such ecological variables were suggested as one of several potential factors influencing residue levels in ring-necked pheasants (W. L. Anderson et al. 1970). The variety of potential variables and their seemingly constant state of flux seem to point up the need for a systems-analysis approach as an aid in understanding the kinetics of pesticides.

One point seems clear. The herring gull population in Green Bay is severely burdened with various chlorinated hydrocarbon residues. Several sublethal effects of such residues are discussed by Keith (1966), Ludwig & Tomoff (1966) and Anderson et al. (1970). If one

considers the average adult weight of Green Bay herring gulls as around 1100 g and the maximum body burden as 300 ppm (wet-weight) DDE and 200 ppm apparent PCB, the micrograms per bird come to around 3.3×10^5 and 2.2×10^5 of DDE and apparent PCB, respectively. If the total breeding and non breeding population in Green Bay is 20,000 birds, then 6.6×10^9 and 4.4×10^9 are the μg's of DDE and apparent PCB present in the entire biomass of resident, Green Bay herring gulls. This amounts to 6.6 kg of DDE and 4.4 kg of apparent PCB, seemingly enough to have ecological consequences.

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SUMMARY

The dynamics of certain chlorinated hydrocarbons were studied over a period of one annual cycle in caged juvenile and wild adult herring gulls from Lake Michigan. Fish, mostly alewives, comprised the major year-round food items in the wild. Alewives were fed to the caged juveniles, and their residues averaged around 3 ppm (wet-weight) DDE,

2 ppm DDT + TDE and 2 ppm apparent PCB. In late fall and early winter, human refuse (including fish) became an additional food source.

Lipid deposition, chlorinated hydrocarbon residues and body weight varied seasonally, as well as food consumption in juveniles where data were available. Fat deposition in caged juveniles followed a pattern similar to that of adults except that amounts were greater. Lipid deposition was generally related to amount of food consumed in juveniles but residues were not.

Juvenile residues showed a continual buildup and eventual, temporary stabilization. Total body-burdens in both age classes were similar after these buildups by juveniles in their 9th month of life. The seasonal variations of residues of DDE and apparent PCB were characterized by two phases in adults and three in juveniles. Juveniles apparently assumed the adult pattern. The maximum body-burdens in both juveniles and adults were attained when lipids were being lost in spring and when adult gonadal activity was presumably at its maximum. This was followed by a return to "equilibrium." The maximum body burdens attained by caged juveniles on a diet of Lake Michigan alewives were 290 mg/kg DDE, 19 mg/kg DDT + TDE and 200 mg/kg apparent PCB. Residues in wild adults at the same time were 300, 4, and 200, respectively. Apparent PCB's seemed to show a greater propensity for accumulation than DDE, although both were highly accumulative. DDE levels apparently resulted from dietary DDE as well as probable conversion from DDT. The extraordinary spring increases in body burden were attributed to changes in the ability of the central compartment (of which liver is a part) to maintain "normal", "equilibrium"-type excretion rates of residues already in the body.

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CHLORINATED HYDROCARBONS AND EGGSHELL VARIATION IN HERRING GULLS

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Our objectives here are to describe normal geographic variation in several eggshell measurements of North American Herring Gulls (Larus argentatus), to report recent eggshell changes in various parts of their breeding range, and to relate these changes to residues of chlorinated hydrocarbons resulting from environmental pollution. It was in 1946 that eggshell changes began in Peregrine Falcons (Falco peregrinus) and Eurasian Sparrow Hawks (Accipiter nisus) in Great Britain (Ratcliffe, 1970). We found that these changes occurred in North America as early as 1947 (Hickey and Anderson, 1968); we lacked the adequate sample of 1946 eggs with which Ratcliffe worked. Ratcliffe (1970) has convincingly discussed the causal link between organochlorine residues in general and recent eggshell thinning for a substantial list of British birds; and experimental verification of the link has been supplied by Heath et al. (1969) and Porter and Wiemeyer (1969).

The problem of normal variation in large Larus gulls is by no means simple, as all reviewers of this group have already brought out. Ingolfsson (1969) has discussed sexual dimorphism in Herring and other gulls; and because of this, all measurements discussed below are those of females. Dwight (1925: 182) described intersubspecific variation in Herring Gulls as follows (wing, tarsus, and culmen measurements, respectively, for each subspecies in mm): argentatus = 384, 58, and 47: smithsonianus = 411, 62, and 50; vegae = 422, 66, and 51; "thayeri" = 395, 60, and 48. Thayer's Gull is considered as a subspecies of Larus

argentatus by the A.O.U. Check-list (1957: 222), but some authors (Rand, 1942; Salomonson, 1950: 319-321; Macpherson, 1961; and Smith, 1966: 5-7) treat it as other than L. argentatus. Snyder (1957: 214) and Moynihan (1959) suggested that thayeri might be a distinct species. In the present paper, we have included the few specimens we examined and have followed the terminology used by Macpherson (1961) and Smith (1966). Dwight (1925:194) considered vegae as the largest of the Herring Gulls. Perhaps a significant observation was that of Snyder (1957: 213), who reported that thayeri averaged slightly smaller than argentatus in the arctic. Smith (1966: 12, 17, 22) gives the above measurements for arctic specimens of Herring Gull from three locations as 419, 63, and 51-52 mm, suggesting that North American Herring Gulls may be slightly larger in the north (compared to Dwight's specimens cited above, which judging from his range description came from south of Hudson Bay). Voous (1959) established that Herring Gulls from Great Britain were smaller in wing-length (sexes combined) than North American specimens (10) of smithsonianus, but his specimens from Fennoscandia were as large, or larger. Harris (1964) reported egg volumes of Herring Gulls from Wales to average around 76 cc, but volumes calculated from the data of Paludan (1951) averaged around 86 cc. Paludan studied Herring Gulls near Bornholm, on the Baltic Sea. These data support Voous (1959), who demonstrated that geographical variation in the European Herring Gull was clinal in nature. The breeding ranges of the North American gulls described above are given in Figure 1 to show the geographical relationships of our various test groups. This map was derived from the A.O.U. Check-list (1957: 221-222), Macpherson (1961), mostly Smith (1966:

7, 91) and only generally from Voous (1960: 147), who considers all North American forms (save possibly vegae, if it breeds in North America) as argentatus. Bent (1921: 124) doubts the validity of Alaskan records of vegae, although such records do not seem unlikely. We have accepted two sets of eggs from St. Lawrence Island because of their proximity to the range of vegae as described by Dement'ev and Gladkov (1951: 531). Some range descriptions of vegae (Dwight, 1925: 181; and A.O.U. Check-list 1957: 222) mention only Siberia.

MATERIALS AND METHODS

DATA SOURCES

The measurements described herein for Herring Gulls comprise those of scientifically collected eggshells from about 65 major museums and private egg collections representing a large proportion of North American collections. The methods we used to measure eggshells and most of our data sources have already been outlined by Anderson and Hickey (1970). Additional details concerning our methods are in Anderson et al. (1970). Data concerning other species of larids were all obtained from the oological collection in the Field Museum of Natural History, Chicago, Illinois; these represent samples from small geographical areas. Other larid eggshells examined included those of Sabine's Gull (Xema sabini), Franklin's Gull (L. pipixcan), Mew Gull (L. canus), Heermann's Gull (L. heermanni), Ring-billed Gull (L. delawarensis), California Gull (L. californicus), Western Gull (L. occidentalis), and Glaucous Gull (L. hyperboreus). Eggshells from two species of Peruvian larids (Peruvian Gull, L. belcheri and Dominican Gull, L.

Figure 1. Breeding range of North American Herring Gulls as determined from various authors. The general geographical areas used to test for geographic variation in eggshells are numbered in accordance with Table 1. Closed circles represent those areas where samples were obtained for chemical analysis.

dominicanus) were collected by Anderson in 1969. These were plotted but not included in any statistical analyses except for Figure 3.

Our recent Herring Gull egg specimens, besides being found in museums and private collections, represented materials collected by us in the course of our studies on Lake Michigan or by cooperators in other areas (Figure 1). Our specimens from 1967 from which we obtained eggshell and residue data are representative of gulleries from Knife River, Minnesota (Lake Superior) and Sister Bay, Wisconsin (Lake Michigan) (collected by us), Roger's City, Michigan (Lake Huron) (collected by J. T. Emlen, Jr. and D. H. Thompson), Block Island, Rhode Island (collected by M. E. Slate), and Penobscot Bay, Maine (collected by W. H. Drury). T. C. Grubb collected our 1969 Herring Gull eggs from Kent Island, New Brunswick. Residues of p,p'-DDE and their relationships to shell thickness, on a colony-to-colony comparison, have already been reported by Hickey and Anderson (1968) but will be further and in more detail related to overall contamination profiles below.

DATA TREATMENT

Statistical methods generally followed those outlined by Steel and Torrie (1960). Our general procedure was to review the literature on geographic variation in Herring Gulls and then to test trends in eggshell volume, empty shell weight, eggshell thickness (including membranes), egg shape, and length/breadth ratios generally against already described trends, if available, in body size or some measurement relating to it. Most of our measurements in other species have been

shown to be a satisfactory general index to body size (discussed by Anderson and Hickey, 1970, in relation to Brown Pelicans, Pelecanus occidentalis; and Anderson et al., 1970, in relation to Common Loons, Gavia immer). In Great Lakes and Atlantic Coast data series we first tested various groups for thinning as they fell into decades (1900-09, 1910-19, etc.). This test showed only highly significant differences in the decades after 1940. However, this did not indicate precisely when changes occurred. Post-1946 data were then broken down into as small groups as possible depending solely on sample distributions. They were not selected except that smaller groups were set up wherever feasible. Consistent nonsignificant differences in pre-1946, decade samples were considered as justification for their eventual combination and assumed biological consistency.

CHEMICAL ANALYSES

The Wisconsin Alumni Research Foundation (WARF Institute, Inc., Madison, Wisconsin) conducted our chemical analyses, using electron-capture gas chromatography (GC). The chromatographic interpretations concerning polychlorinated biphenyls (PCBs) are ours, but are generally based on methods described by Risebrough et al. (1969) and Reynolds (1970). WARF chemists employed the methods outlined by the U.S. Food and Drug Administration (1965-68) for analysis of chlorinated-hydrocarbon pesticides. Further modifications used for us by WARF to confirm p,p'-DDT and p,p'-TDE are described by Anderson et al. (1969), and our interpretations regarding PCBs are described by Anderson and Hickey (in preparation). The compounds in our analyses included

p,p'-DDE, apparent PCB, p,p'-TDE, p,p'-DDT, heptachlor epoxide (HE), and dieldrin. All but PCBs are known to be insecticides or insecticide-derived materials. Further data on PCB sources and uses as well as analytical techniques are reviewed by Reynolds (1970).

At least one PCB peak is known to potentially interfere with p,p'-DDE on the DC-200 column of the GC in Lake Michigan Herring Gull samples, but interference is reduced to a minimum by the methods WARF used for quantification (dilution) and by the very high proportions of DDE present. Interference is potentially more critical, however, in samples such as those we analyzed from Maine and Rhode Island, where DDE was present in much less amounts in relation to apparent PCB, compared to our Great Lakes samples. We found that standard, peak-height quantifications of p,p'-DDE had to be multiplied by a factor of 0.80 for Rhode Island specimens and by 0.86 for Maine specimens, assuming that the "hidden" peak was constant in relation to the PCB peak that we could see just preceding DDE in retention time. Because of the potential variability on a ppm wet-weight basis due to possible desication in addled eggs and water losses in incubated eggs, we express here all residues on a ppm lipid basis unless otherwise specified. We consider such values as representative of concentrations in, and possibly affecting, the female at the time of eggshell deposition (Enderson and Berger, 1970; Vermeer and Reynolds, 1970; and others).

RESULTS AND DISCUSSION

GEOGRAPHIC VARIATION

The intersubspecific variations in several eggshell measurements

(Table 1 and Figure 2) seemed generally to follow other variations in Herring Gulls, as described above. These variations are most likely clinal in nature, as discussed by Voous (1959) and Mayr (1965: 361-364). The geographical subdivisions suggest a cline, but also evident in all areas is the high degree of variance which tends to mask differences over the entire range (Figure 2). Where we had larger samples, however, differences became more apparent. Because of the apparently high variance in Herring Gull eggshells, especially in relation to those in other species we have studied, it seems that larger samples might be needed to describe differences for this species more precisely. It may be that variations within individual females (Harris, 1964; Coulson et al., 1969; Vermeer, 1969) tend to mask or reduce significance of differences between local populations. An analysis of variance to test whether differences did or did not occur in the North American "populations" (or geographical test units) gave highly significant F-values: $F_{wt} = 12.21$, $F_{vol} = 7.51$, and $F_{th} = 7.37$, when $F(P0.005) = 2.90$. A Duncan's new multiple-range test for differences in eggshell volumes of the North American test units of Herring Gulls showed clinal overlap but suggested the distinctness of northern, Atlantic-Interior, and Great Lakes populations; the data were not uniform enough nor sample sizes large enough for any further distinctions (means not significantly different from one another are underscored, reading from left to right):

Arctic Interior St. Lawrence Atlantic Great Lakes

TABLE 1

GEOGRAPHICAL VARIATION IN THE EGGSHELLS OF HERRING GULLS[1/]

Geographical area (species-subspecies)[2/]	Sample size[3/]	Shapes:[4/] PY	OV	SE	Variable ($\bar{x}$ ± 95% CL) Weight (g)	Volume (cm^3)	Thickness (mm)	L/B[5/]
1. No. islands of Canada (*Larus thayeri*)	9(7)	0	9	0	6.94±0.51	89.4±8.1	0.404±0.016	1.48±0.07
2. Eastern Siberia coast (*L. argentatus vegae*)	13(10)	0	13	0	6.52±0.42	91.0±5.9	0.386±0.015	1.40±0.02
3. Arctic-Taiga, Canada (*L. a. smithsonianus*)	103(94)	1	88	14	6.52±0.11	89.0±1.4	0.384±0.004	1.45±0.01
4. No. Am. interior lakes (*L. a. smithsonianus*)	56(53)	0	47	9	6.32±0.14	88.3±1.8	0.384±0.006	1.46±0.02
5. No. Am. Great Lakes (*L. a. smithsonianus*)	456(369)	4	388	64	6.07±0.06	84.7±0.7	0.375±0.002	1.46±0.01

TABLE 1 continued.

TABLE 1 continued.

6. St. Lawrence R. system (L. a. smithsonianus)	41(15)	0	37	4	6.36±0.20	87.3±2.7	0.381±0.009	1.44±0.02
7. No Am. Atlantic Coast (L. a. smithsonianus)	598(513)	2	522	74	6.29±0.05	86.9±0.6	0.372±0.002	1.44±0.01
8. Iceland (L. a. argentatus) 6/	9(6)	0	7	2	5.79±0.53	81.4±6.7	0.377±0.013	1.41±0.05
9. English Coast (L. a. argentatus)	101(47)	0	89	12	5.86±0.09	81.8±1.2	0.375±0.006	1.44±0.01

1/ L. thayeri is included for comparative purposes, or as some authors would prefer, as the northernmost subspecies of Herring Gull.

2/ See Figure 1, the small sample of vegae eggs was the product of three collectors: Capt. H. H. Bodfish, e. Siberian coast; J. Koren, mouth of Kalyma River, n. e. Siberia; and G. L. Kennedy, St. Lawrence Island. Arctic-Taiga included specimens from the Northern Islands identified as smithsonianus; those that were not identified were dropped from the data analysis. Interior lakes included all lakes generally south of tree line not associated closely with the Great Lakes, and generally west of James

TABLE 1 continued.

TABLE 1 continued.

Bay. Great Lakes samples included all but Lake Ontario (no specimens). St. Lawrence River specimens included that area and associated inland lakes. The Atlantic coast specimens included eggshells from the Gulf of St. Lawrence.

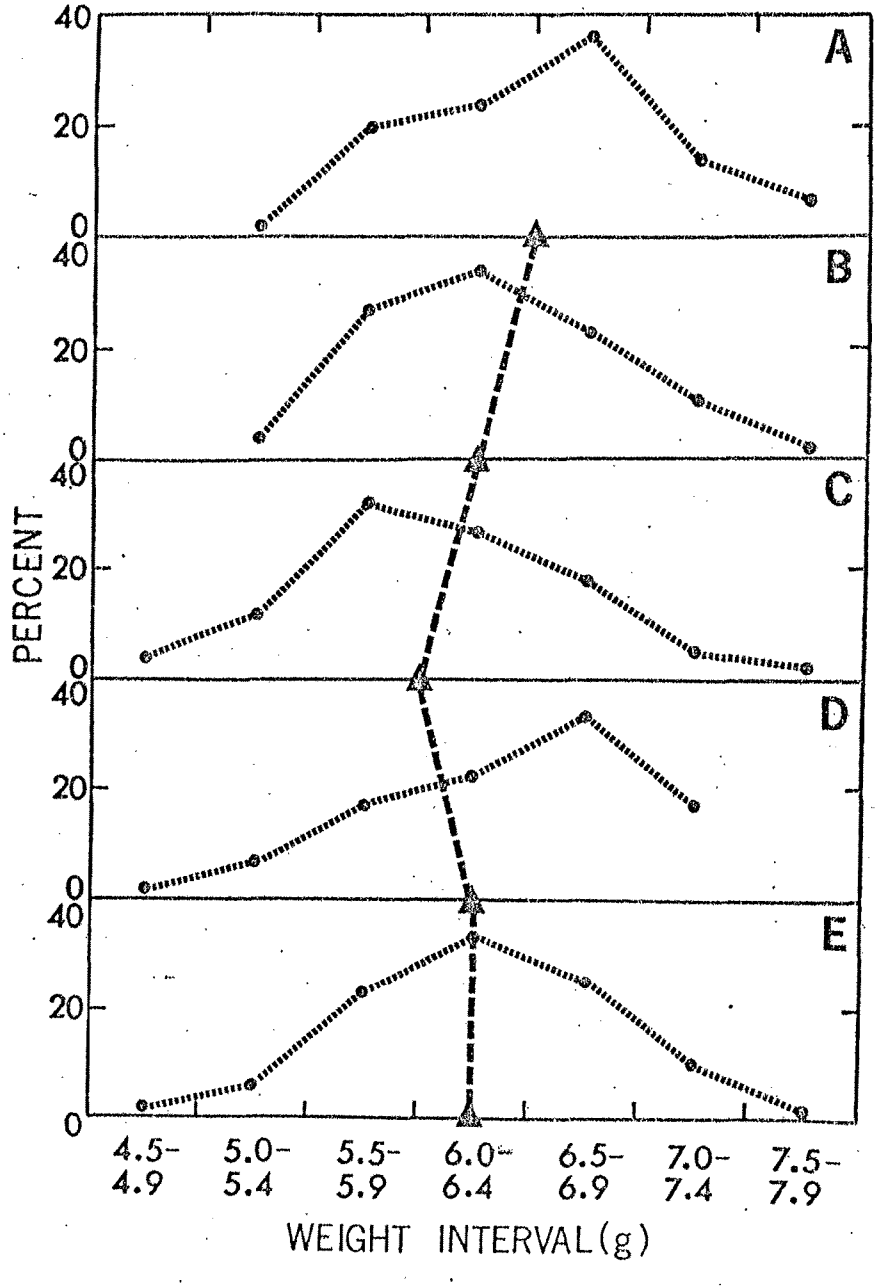
3/ Numbers in parentheses are for thickness only.

4/ As described by Palmer (1962: 13), PY = pyriform, OV = oval, SE = subelliptical.

5/ Length: breadth.

6/ Subspecies designation from Vaurie (1964: 468).

Figure 2. Frequency distributions of eggshell weights of North American Herring Gulls from various geographical regions. A = arctic-taiga, B = interior, C = Great Lakes, D = St. Lawrence River system, E = Atlantic Coast.

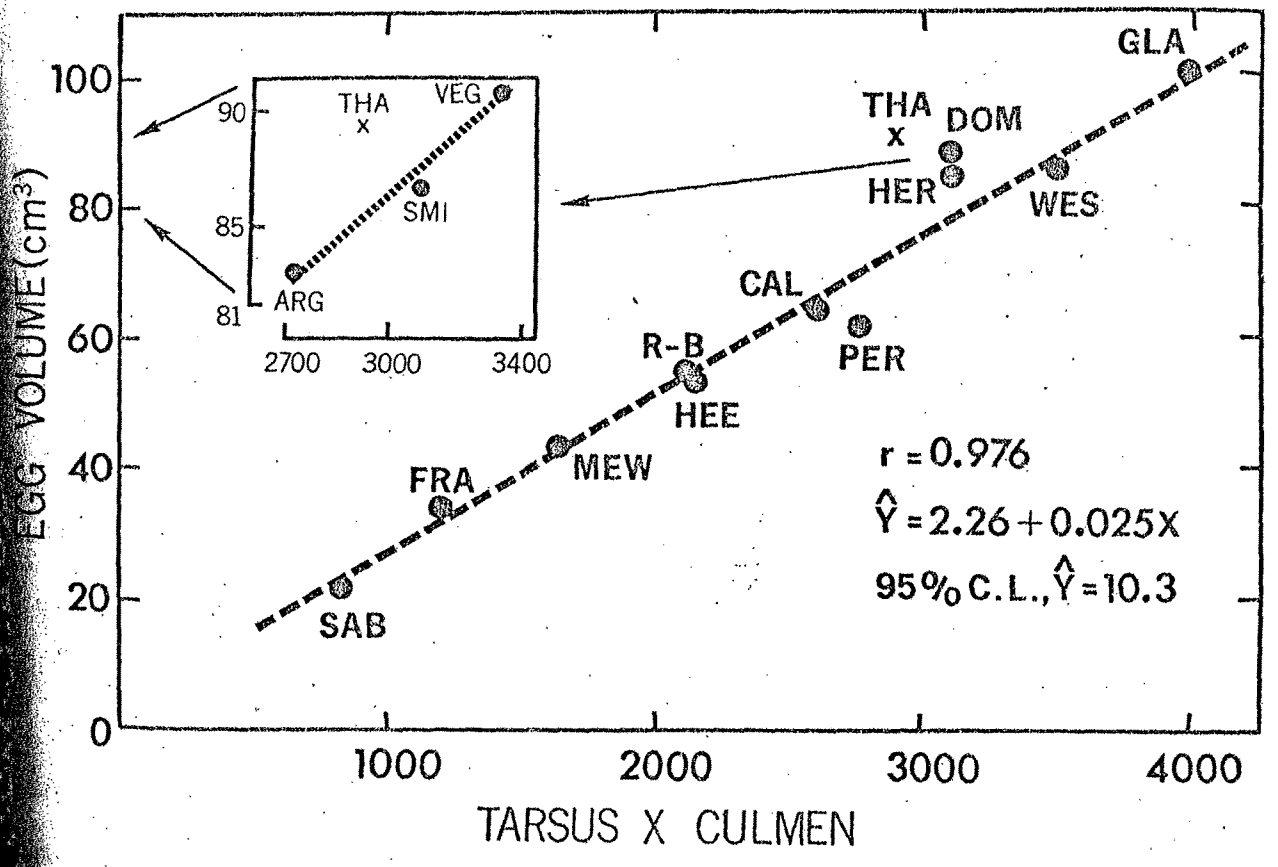


Because of the likelihood of clines, we included intermediate areas in our presentation of the data (Table 1), although they were not significantly different from adjacent areas. Banding data, reported by Gross (1940), suggest that Kent Island Herring Gulls tended to "cling" to the Atlantic Coast, whereas Great Lakes birds tended to follow lake shores and water courses. These data support the idea of at least limited population isolation. Smith (1959) further reported that Great Lakes birds followed somewhat distinct dispersal patterns and that, after their second year, most birds tended to remain on the Great Lakes year-round within 300 miles of their breeding colony. Olsson (1958: 151-155) reported similar findings for Herring Gulls from Fennoscandia. Data are very much needed on interior and arctic Herring Gulls from North America.

INTER- AND INTRASPECIFIC EGG RELATIONSHIPS

Lack (1966: 293) believes that relative egg size is a specific characteristic and mainly a matter of heredity on an interspecific basis. Eggshell volume in the twelve species of larids that we examined relates closely to our index of body size (tarsus X culmen, in mm) on inter- and very likely on intraspecific bases (Figure 3). Amadon (1943) pointed out that egg size was generally a nonlinear function of body size in small birds, as expressed by the equation, $Y = bX^a$, where a is a constant expressing the ratio of egg size versus body size increase in a series. He found a to be constant at the "intermediate" taxonomic category (subfamily) in small birds. If one assumes a similar constancy of a in the larids we examined, the straight-line relationship on a nonlog scale in Figure 3 seems reasonable. Since the 95% confidence

Figure 3. Eggshell volume as a general function of index to body size (in mm) in 12 species of larids and 3 subspecies of Herring Gulls (VEG = vegae, SMI = smithsonianus, and ARG = argentatus). The correlation coefficient (r) was significant at $P<0.001$. Additional abbreviations are as follows: SAB = Sabine's Gull, FRA = Franklin's Gull, MEW = Mew Gull, HEE = Heermann's Gull, R-B = Ring-billed Gull, CAL = California Gull, PER = Peruvian Gull, HER = Herring Gull, THA = Thayer's Gull, DOM = Dominican Gull, WES = Western Gull, GLA = Glaucous Gull.



limits (C L) of the intercept overlapped zero considerably, it was not significantly different from zero (Figure 3), and the simple equation, $Y = bX$, seems applicable, b being the general constant relating eggshell volume to body size in larids. Additional factors, such as clutch-size variation deviating from the familial mean trend, might be expected to slightly change the value of a for a given species. In this instance, our small sample of Thayer's Gull fell farthest from the fitted line. The general relationship and the closeness of fit for the remainder of the species (Figure 3) further support the view that eggshell volume (and thus likely egg weight) is fairly constantly related to body size in closely related forms (Amadon, 1943). Eggshell thicknesses and weights were closely related to their eggshell volumes in all the species we examined (r, comparing volume and thickness = 0.968, $P < 0.001$, $\hat{Y} = 0.0025X + 0.183$; r, comparing volume and eggshell weight = 0.995, $P < 0.001$, $\hat{Y} = 0.079X + 0.387$).

RECENT EGGSHELL CHANGES

Ratcliffe (1970) has documented that eggshell changes have occurred since 1945-46 in certain species of British birds. He validly divided test periods into "late" and "early" (Mountford, 1970), presenting pre- and post-1946 eggshells to demonstrate this phenomenon. We obtained data on 295 post-1946 eggshells.

Demonstrable eggshell changes occurred in most of our more recent samples, although many represented what we considered to be minor changes, that is, decreases of not over 10-15% (Table 2). Our best histories came from Lake Michigan and Lake Huron. On the latter, 1947-48 eggs showed no changes, but by 1951-58 changes were detectable. They

TABLE 2

CHANGES IN INTACT EGGSHELLS OF NORTH AMERICAN HERRING GULLS SINCE 1946

		Eggshell weight (g)				Shell thickness (mm)			
Geographical Area	Date	No.	Mean	t-value[1]	Change[2]	No.	Mean	t-value[1]	Change[2]
Arctic	1954-62	12	6.12	2.40**	-6%	3	0.397	1.07	-3%
L. Superior	1967	14	5.64	2.48**	-7%	14	0.349	4.13++	-7%
L. Huron	1947-48	14	5.93	0.79	-2%	14	0.375	0.00	0%
L. Huron	1951-58	19	5.70	2.49**	-6%	19	0.350	4.48++	-7%
L. Huron	1960-66	19	5.90	1.08	-3%	7	0.333	4.79++	-11%
L. Huron	1967	10	5.63	2.15*	-7%	10	0.346	3.94++	-8%
L. Michigan	1953-56	9	5.97	0.47	-2%	3	0.343	2.40**	-9%
L. Michigan	1960	19	5.50	3.78++	-9%	no data	-	-	-
L. Michigan	1962	6	5.63	1.65	-7%	no data	-	-	-

TABLE 2 continued.

TABLE 2 continued.

L. Michigan	1964	9	5.00	4.97++	-18%	9	0.317	7.49++	-15%
L. Michigan	1965	5	4.94	3.90++	-19%	3	0.307	5.09++	-18%
L. Michigan	1966	12	5.54	2.82+	-9%	12	0.335	5.96++	-11%
L. Michigan	1967	23	5.58	2.71+	-8%	23	0.339	5.55++	-10%
L. Michigan	1968	59	5.54	5.84++	-9%	59	0.338	11.06++	-10%
L. Michigan	1969	24	5.66	3.01+	-7%	24	0.345	6.09++	-8%
Rhode Island	1967	10	6.24	0.26	-1%	10	0.380	1.11	+2%
Penobscot Bay, Me.	1967	13	6.30	0.07	0%	13	0.379	1.11	+2%
Kent Island, N.B.	1963	9	5.62	3.39++	-11%	9	0.368	0.53	-1%
Kent Island, N.B.	1969	9	5.56	3.66++	-12%	9	0.343	3.77++	-8%

[1] Comparisons are with pre-1946 data from appropriate geographical areas as given in Table 1. The nearest significance levels of the probabilities of difference are indicated as follows: * = $P<0.05$;

TABLE 2 continued.

TABLE 2 continued.

** = $P<0.02$; + = $P<0.01$; ++ = $P<0.001$.

[2] Percent changes are percentages from the pre-1946 means.

seem to have remained at generally less than a 10% change. The changes on Lake Michigan prove even more interesting (Table 2). They seem to have paralleled Lake Huron into the early 1960s although we have no data for 1961 or 1963. In 1964 and 1965, eggshell changes were 15% or greater. It is perhaps significant that this period was one of frequent and readily observed egg-breakage on Lake Michigan study areas (Keith [1966] for 1964 and Ludwig and Tomoff [1966] for 1965, each on opposite shores of Lake Michigan). Eggshell fragments from three broken eggs incidentally picked up by Keith in 1965 measured 0.16, 0.28, and 0.34 mm, averaging 0.26 mm, 31% thinner than pre-1946 eggshells. Nine broken or cracked eggs collected by Anderson in 1968 averaged 0.34 mm, not different from our random sample of the colony that year (Table 2). Data are critically needed on frequencies of egg breakage at different eggshell thicknesses. No precise quantitative data of this type were obtained in our studies, but in 1969, when egg breakage was the least seen by us in 4 years of visits to the colonies, about 5-10% of the nests contained obviously broken eggs (other than eggshells possibly broken open by predation), and about 20% of the nests had loose, uncrushed eggs nearby. Keith (1966) estimated readily observable egg breakage at about 11-24% in 1964. In general, it seems that eggshell thinning on the order of and greater than 15-20% is associated with readily observable breakage.

Eggshells of California Brown Pelicans (including the relatively constant membranes) averaged 53% thinner than "normal" in 1969, and such changes were associated with obvious, virtually total failure in reproduction (Risebrough et al., 1970 and J. O. Keith et al., 1970). Ratcliffe (1970) reported that eggshell changes roughly on the order of 10-20% were associated with declines in populations of some British raptors,

but such eggshells represented those that had "survived" to be taken by egg collectors. Hickey and Anderson (1968) showed changes of roughly 18-25% circumstantially associated with declining species of American raptors. Both studies associated eggshell thinning with reported frequent egg breakage, lowered reproductive success, and high residues of pesticides.

The 1964 levels of p,p'-DDE reported by Keith (1966) for Lake Michigan Herring Gull eggs are the highest reported in 7 years of monitoring the same population. Levels were still high, however, in relation to other North American Herring Gulls in 1967 (Hickey and Anderson, 1968). Eggshell breakage still continues on Green Bay, but reproductive success is apparently high enough to produce reduced but bandable numbers of young in recent years (H. C. Wilson, personal communication). Whether or not this population is presently reproducing enough to maintain stationary numbers is a matter open to question; it was not in 1964 (Keith, 1966). Keith reported a mean clutch size of 2.11 as compared to our best estimate of 2.72 in 1968 and 2.81 from southern, Atlantic, and interior egg data. Although there is a tendency for Herring Gulls to return to their natal colony (Ludwig, 1963), there is no reason to doubt, if one segment of the population is declining, colonization by gulls from other, more successful, areas of the Great Lakes. Herring Gull control in Massachusetts colonies was generally unsuccessful from 1942 to 1952, presumably because of such immigrations from more successful colonies outside the state (Drury, 1963). Great Lakes Herring Gulls have generally undergone a recent population increase, probably due to a recently developed superabundant food source, the alewife (Alosa pseudohaneugus) (Ludwig, 1966), which would tend to lessen the normal

regulating effects of limited food supply (Lack, 1954: 141-153).

Our Atlantic samples suggested only local eggshell changes on the East Coast (Table 2). Since these populations have been under control measures since the early 1940s--they are also the beneficiaries of a superabundant food resource, human or human-associated refuse--and have increased in recent years (Gross, 1951; Drury, 1963; Kadlec and Drury, 1968), the interpretations of shell-thinning become nearly impossible. Eggshell data suggest, nonetheless, the presence of only low amounts of thin-eggshell-inducing compounds such as p,p'-DDE (see Heath et al., 1969) in most of the samples. Decreased eggshell weights or thicknesses from Kent Island (Table 2) may even reflect a higher frequency of second clutches in these birds, due to the control measures. Residue analyses are needed from Kent Island before any conclusions can be made regarding eggshell changes in that area.

CHLORINATED HYDROCARBON RESIDUES, 1967

Highly significant ($P<0.005$) differences (analysis of variance to test whether or not geographical residue-differences were present) were found for DDE, DDT + TDE, apparent PCB, HE, and dieldrin as well as eggshell weights and thicknesses. DDE/PCB ratios showed the same highly significant differences, which suggest varying contamination patterns, especially when one compares Atlantic and Great Lakes populations (Table 3, Figure 4). Apparent PCB increased in relation to DDE in the East, although levels of both decreased considerably outside the Great Lakes (Table 3). The calculated mean egg volume ($\pm$ S.E.) for the three colonies from the Great Lakes was 85.4 ± 1.3 cm^3. That for three Atlantic colonies (1969 Kent Id. sample added) was 87.5 ± 1.3 cm^3.

TABLE 3

VARIATIONS IN RESIDUE LEVELS OF CHLORINATED HYDROCARBONS (LIPID BASIS IN EGG) AND EGGSHELLS IN FIVE BREEDING COLONIES OF HERRING GULLS IN 1967

	Colony location:[1/]				
Variable (unit)	Lake Superior (n=14)	Lake Michigan (n=13)	Lake Huron (n=10)	Rhode Island (n=10)	Maine (n=13)
Percent lipid in eggs	7.29±0.93	7.81±0.64	7.83±0.84	7.92±0.70	8.56±0.55
p,p'-DDE (ppm)	616.0±206.6	972.5±252.4	645.4±258.2	32.5±14.6	20.1±7.2
p,p'-DDT + p,p'-TDE (ppm)	16.6±8.6	21.1±6.1	32.3±14.5	6.9±3.1	1.3±0.7
Apparent PCB ("ppm")	595.6±137.6	812.2±116.4	720.1±194.4	184.2±85.3	45.0±22.9
Heptachlor epoxide (ppm)	11.1±2.5	17.9±4.9	19.2±6.4	1.7±0.6	0.6±0.3

TABLE 3 continued.

TABLE 3 continued.

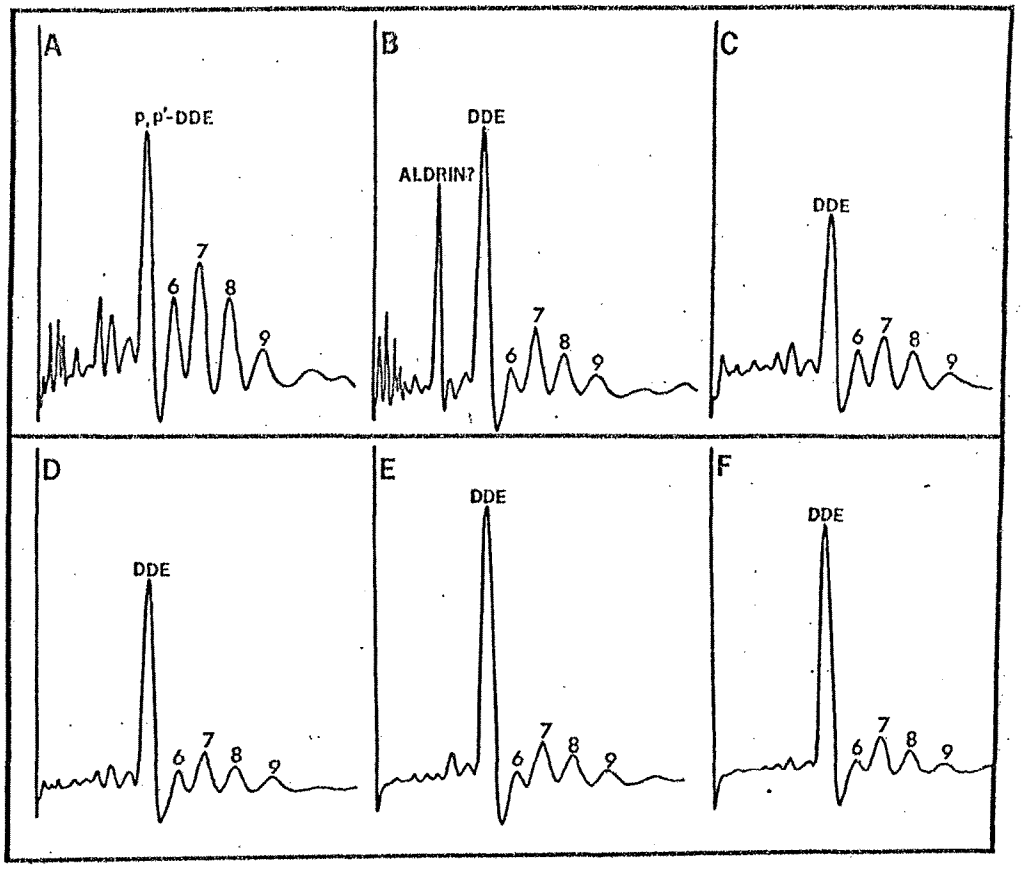
Dieldrin (ppm)	7.1±1.7	10.4±2.4	7.0±2.6	1.2±0.7	0.4±0.1
DDE/PCB ratio[2/]	1.00±0.13	1.17±0.14	0.87±0.24	0.18±0.03	0.58±0.19
Eggshell weight (g)	5.64±0.35	5.57±0.41	5.63±0.36	6.24±0.28	6.30±0.32
Thickness index[3/]	1.59±0.09	1.57±0.08	1.61±0.08	1.73±0.05	1.74±0.08
Thickness (mm)	0.349±0.014	0.339±0.012	0.346±0.014	0.380±0.008	0.379±0.009
Percent change-thickness	-7%	-10%	-8%	+ 1%	+ 1%

1/ Values are means ± 95% confidence limits, n represents eggs from individual females.

2/ Computed as the mean of the individual ratios.

3/ Derived by Ratcliffe (1967, 1970).

Figure 4. Variations in chromatographic patterns of extracts from Herring Gull eggs representing different colonies. These chromatograms represent injections of different dilutions and are meant only to show qualitative differences between DDE and the numbered apparent PCB peaks in general linear range of response of the electron-capture detector. A = Rhode Island, B and C = Maine (B suggests the possible presence of aldrin), D = Lake Huron, E = Lake Michigan, and F = Lake Superior.



These are not unlike the pre-1946 eggshell volumes (Table 1) and suggest (1) that eggshell changes did not importantly involve changes in volume and (2) that geographical variation in volume can therefore probably still be detected with adequate sample sizes. When correlation matrices were run with data on individual eggs, we found significant negative relationships between DDE, DDT + TDE, and apparent PCB and eggshell thickness and other measurements relating to thickness (Table 4). This, of course, casts doubt as to which residue might be most importantly involved, or if all are not involved to some degree. As DDT + TDE was related to DDE (r = 0.537), their relationship to eggshell thickness may reflect a cause-effect relationship or a general association with "DDT-family" residues. Heath et al. (1969) have experimentally produced eggshell thinning in the Mallard (Anas platyrhynchos) with a low dietary intake of DDE, and Porter and Wiemeyer (1969) have obtained similar effects in the American Sparrow Hawk (Falco sparvarius) with p,p'-DDT combined with dieldrin. Bitman (1970) and Bitman et al. (1969) have also shown a similar effect with both o,p'-DDT and p,p'-DDT in Japanese Quail (Coturnix coturnix), and Lehner and Egbert (1969) have demonstrated minor and levelling eggshell changes in Mallards with dieldrin alone. On the other hand, Dahlgren and Linder (1970) were unable to induce eggshell thinning in Ring-necked Pheasants (Phasianus colchicus) with dieldrin, nor did injections of dieldrin succeed with Ringdoves (Streptopelia risoria)(Peakall, 1970a). Peakall did, however, induce significant eggshell thinning in Ringdoves injected with p,p'-DDE.

In attempting to formulate a hypothesis from our field data, and to eliminate individual variability, we arbitrarily set up six class intervals of shell thickness and calculated weighted means for each;

TABLE 4

CORRELATIONS BETWEEN VARIOUS EGGSHELL VARIABLES

AND RESIDUES OF DDT-COMPLEX AND APPARENT PCB

	Residue (ppm lipid basis)[1]		
Variable	p,p'-DDE	p,p'-DDT + p,p'-TDE	Apparent PCB
Eggshell wt. (g)	-0.484***	-0.302**	-0.555***
Thickness (mm)	-0.646***	-0.427***	-0.700***
Thickness index[2]	-0.505***	-0.309**	-0.534***

[1] Significance levels are marked as follows: ** = $P<0.01$, *** = $P<0.001$.

[2] Devised by Ratcliffe (1967, 1970): (weight in grams X 10)/(length X breath in cm).

likewise, weighted means of residues were calculated. In this way, we felt that we were basically looking at the variations relating to thickness as a result of the residues, although our degrees of freedom were considerably reduced. Simple correlations (r) of the means were as follows: DDE = -0.97, $P<0.01$; apparent PCB = -0.91, $P<0.02$. F-tests with the regressions gave values of 56.7 for DDE and 20.3 for apparent PCB, significance levels $P<0.005$ and $P<0.01$, respectively. Multiple-regression analysis (Steel and Torrie, 1960: 277-304) with DDE and apparent PCB gave an F-value of 22.9, $P<0.025$; $R^2 = 0.94$, $P<0.05$. Simple exponential (curvilinear) functions in both types of regressions failed to improve any of the relationships, although the higher significance levels in the F-tests suggested that the relationships were not perfectly linear in the ranges we tested. Because the significance levels were decreased with apparent PCBs alone and with the two residues considered together, it seems that more variation in eggshell thickness can be accounted for by DDE than apparent PCB, but that both seem potentially important. Although DDE/PCB ratios were significantly different between the Great Lakes and Atlantic Coast Herring Gulls (Table 4), the actual levels were different enough between the colonies so that such ratios shed little light concerning eggshell changes. Vermeer and Reynolds (1970) found a significant negative relationship between DDE and eggshell thickness in Great Blue Herons (Ardea herodias), but not PCB. DDE + TDE alone were related in field data to eggshell thinning in White Pelicans (Pelecanus erythrorhynchos), but both DDE and apparent PCB showed significant negative correlations in Double-crested Cormorants (Phalacrocorax auritus), both species coming from identical breeding grounds (Anderson et al., 1969). Egg residues

were probably a result of dissimilar nonbreeding-area exposures (potentially geographical-area differences as well as food-habits differences), however. It may be that DDE and PCB interact either positively or negatively, when both are present. For two insect species, Lichtenstein et al. (1969) have predicted biological interactions of PCBs and other synthetic chemicals in nature on the basis of interactions in tests with PCBs, dieldrin, and DDT. About all that we can conclude from our data here and the experimental evidence already cited is that DDE residues are important in eggshell thinning and that apparent PCBs are suspect.

COMPARISONS WITH OTHER HERRING GULLS

It seems that Great Lakes Herring Gulls contain the highest chlorinated hydrocarbon residue levels in eggs reported for that species. Atlantic Coast samples are certainly lower (Table 3). Ludwig and Tomoff (1966) reported DDE levels in eggs (ppm wet-weight) from several colonies northeastern on Lake Michigan as averaging from 103 to 138 ppm ($\underline{n}$ = 32, 4 pools); no estimations were given for PCBs, but "DDT" levels (assuming the same DDE/PCB ratio as found in the Lake Michigan samples reported here, Table 4) suggest residues of apparent PCB at around 100 "ppm". These convert to around 1,500 ppm on a lipid basis if one assumes a general lipid level of 8% (Table 4, and Vermeer and Reynolds, 1970). Keith's (1966) wet-weight mean of 202 $\pm$ 34 ppm DDE for 1964 in Green Bay eggs converts to 2,525 ppm lipid basis. Chlorinated hydrocarbons in British Herring Gulls reported by More and Tatton (1965) ranged from 0.3 to 0.9 ppm, or about 4 to 11 ppm lipid basis. Vermeer and Reynolds (1970) reported that levels of DDE in Herring Gulls from interior Canada varied

from 2.7 (n = 1 colony) to 14.6 ppm wet-weight (mean of 6 colonies), or roughly 34 to 183 ppm lipid basis. These levels are generally intermediate between Atlantic and Great Lakes birds.

ABILITY OF HERRING GULLS TO "TOLERATE" RESIDUES

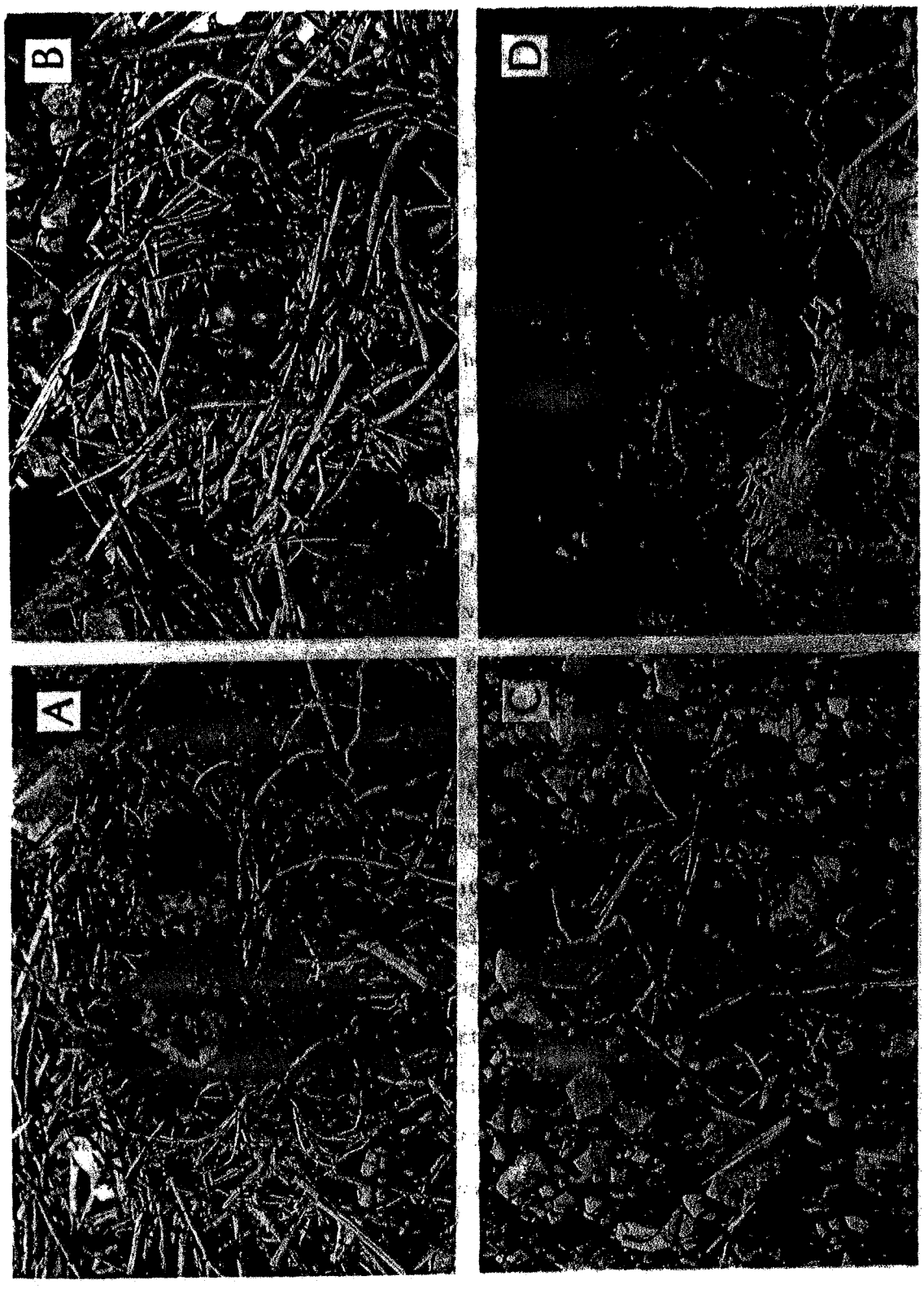
Why do Lake Michigan Herring Gulls, despite their high egg residues of chemical pollutants, show levels of eggshell thinning generally less than those of many other species which have similar or lower residues in their eggs (see Risebrough et al., 1970; Keith et al., 1970; Fyfe et al., 1969; Enderson and Berger, 1970, Berger et al., 1970; and Vermeer and Reynolds, 1970)? Partial explanation when data are comparable at one end of the curve which compares chlorinated hydrocarbons and thickness may come from the nonlinearity of effect of DDE on eggshell thickness toward the higher levels, as proposed by Risebrough et al. (1970), Peakall (1970b), and as suggested by Vermeer and Reynolds (1970). Otherwise, poor general comparisons between species may suggest interspecific differences in susceptibility. The results of D. K. Wetherbee (mentioned in Drury, 1963) suggest that Herring Gulls have an exceptional ability to detoxify many chemosterilants.

If dietary intake of chlorinated hydrocarbons is more closely related to eggshell effects than to body or egg-burden at time of laying as suggested by Bitman (1970) in short-term tests comparing o,p'-DDT and p,p'-DDT, it is conceivable that physiological peculiarities in the annual cycles of birds might result in nonproportional (but diet-related) deposition of high or low residues in the eggs in relation to eggshell thinning.

The population effects of egg breakage in wild populations may also possibly and secondarily involve compensatory adjustments in the survival rates of both juveniles and adults; and they almost surely will

be found to vary in an interspecific fashion. The critical level of thinning seems logically associated with the behavioral traits of nest and incubation behavior characteristic of various groups of birds. Normal thickness-volume ratios for eggshells which are characteristic of taxonomic groups of birds may be important in interspecific differences of susceptibility to eggshell thinning. For example, this ratio in Great Lakes Herring Gulls (Table 1) was 225.9; that for grassland Prairie Falcons (Falco mexicanus)(D. W. Anderson and J. J. Hickey, unpublished) was 119.9. These ratios seem relatively constant between various groups of birds and may be related both to egg placement and nesting substrate. Murphy (1936: 1068, citing Bennett, 1920) comments on the general fragility of the eggshells of Dominican Gulls (see Figure 3 for its relationship to other species of gulls we studied) and its ability to hatch young, even from cracked and dented eggshells. J. A. Keith in 1964-65 and D. W. Anderson in subsequent years have observed that Lake Michigan Herring Gulls seem to have a remarkable ability for at least some embryonic development in their eggs, despite flaking away on large portions of many of the shells (Figure 5d). Many eggs are also found with longitudinal cracks, their fresh contents drained away onto the ground. Such eggshells often appear perfectly intact until handled (Figure 5b). Eggshells in domestic poultry are known to be weakest immediately after laying and when wetted (Tyler and Geake, 1964), and it may be that such eggshells are broken at this critical stage. Many various "micro-circumstances" undoubtedly characterize variations in eggshell breakage on the Green Bay gulleries, normal breakage probably being compounded by the presence of environmental pollutants.

Figure 5. Examples of Lake Michigan Herring Gull nests. A. Well built nest with 2 young; May 1970. B. Well built nest with 3 apparently intact eggs; however, all three were cracked and partly drained from underneath; May 1970. C. Poorly built, late-season nest with an unincubated egg, broken as female flushed from nest; May 1970. D. Flaked egg with partly developed, dead embryo within; nearly half the eggshell had been chipped away; May 1969.



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SUMMARY

Measurements of eggshells of Herring Gulls collected prior to the mid-1940s were found to vary geographically, this variation probably being best described as clinal in nature. These variations were most closely related to indices of body size, as described by other authors. Nearly distinct geographical groupings of eggshell volume and other measurements involved arctic and northern, interior-Atlantic, and Great Lakes populations of Herring Gulls in North America. Eggshell volume was also shown to relate generally to body size in ten other species of larids. Eggshell weight and thickness were generally related to eggshell volume.

Recent eggshell changes (dated back to the early 1950s in our samples from lakes Huron and Michigan), mainly in eggshell thickness and empty weight, were demonstrated up through 1969 in some populations. The 1967 eggshell thinning was evident in Great Lakes specimens, but not in many eggs collected on the Atlantic Coast. Levels of chlorinated hydrocarbons were significantly less in the Atlantic Herring Gull eggs. DDE/apparent polychlorinated biphenyl (PCB) ratios varied as well, with apparent PCB increasing in relation to DDE as one proceeds out from Lake Michigan. Actual levels, however, of both DDE and apparent PCB decreased considerably outside the Great Lakes. The eggshell changes showed a highly significant negative relationship with residues of p,p'-DDE, a metabolite of p,p'-DDT, as well as apparent PCBs. The role of PCBs in eggshell thinning and embryonic mortality remains to be determined. The most extreme eggshell thinning recorded in Green Bay Herring Gulls occurred in 1964 and 1965 when obvious reproductive failures occurred, shell thinning in intact eggs approached 20%, and residues of DDE in the eggs were highest (around 2,500 ppm lipid basis). There is limited evidence that Herring Gulls may not be as susceptible to eggshell-thinning as reported for other species.

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Eggshell Changes in Certain North American Birds

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INTRODUCTION

In this paper we will attempt to add to the current knowledge of chemical pollution by testing the hypothesis first described by Ratcliffe (1967, 1970) that eggshell changes discovered in nine species of British birds have also occurred in North America. We plan to do this by (1) reviewing studies already published or in press and (2) by reporting our own study of the eggshells of 25 species in virtually all the major museum and private egg collections in Canada and the United States.

The 25 species selected by us and our collegues are a biased sample. Some were selected because of their known or suspected high residue levels of chlorinated hydrocarbons, others because of their known or suspected

population decreases and still others because their populations were known or suspected to be stationary or possibly increasing. It became necessary to work with large-sized species because of the fragility of small eggshells, and we in no way wish to present data here to be considered as a representative cross-section of North American birdlife.

METHODS AND MATERIALS

Our own studies have involved 35,017 eggshells. We propose here to summarize our data on 3,004 of these--collected after 1946--and to compare them to 20,654 collected prior to 1947. Our laboratory methods have generally followed those of Ratcliffe (1967) except that we also used a micrometer to measure eggshell thickness (which included the firmly attached membranes) in a fraction of the eggs which had holes as large or larger than 2 mm (Anderson & Hickey, 1970). We compared Ratcliffe's (1967) thickness-index measurements to actual thickness in nine species representing ten geographical regions (Table 1). These tests were run on 100 eggshells from each group and were randomly selected from a larger pool of data. Correlation coefficients were all highly signficant ($P < 0.001$), and therefore we consider thickness index as a reliable and independent estimate of thickness. Ratcliffe defines thickness index as weight of shell in mg divided by the product of length and breadth in mm.

As expected from a continent-wide study, many of the species we examined showed clinal variation in their eggshell measurements (see Anderson & Hickey, 1970; Anderson et al., 1970a, 1970b). We have grouped state and provincial samples together only when they failed to have statistically significant differences at the 95% level. We did, however, initially divide Texas, California, British Columbia, Quebec, Northwest Territories and Alaska into smaller geographical units before carrying

out such tests. In addition, specific collection sites were sometimes used to divide geographical units further on an ecological basis. It is possible that the groupings by region shown in our tables should be further broken down when larger samples become available for statistical analysis. It is also probable that certain geographical groupings might be further combined.

Potential biases exist in egg collections, as Storer (1930) has pointed out. We regard improperly cleaned eggshells as unlikely or easily detected (see Anderson & Hickey, 1970) in the well-curated collections we examined; their occurrence, if undetected, would of course affect any decreases in shell weight or thickness that we encountered. Major eggshell changes leading to an early or almost immediate breakage by the parent birds appear to have at least occasionally taken place in at least the last decade. Risebrough et al. (1970), Keith et al. (1970) and Jehl (1969) report eggshells of Brown Pelican (Pelecanus occidentalis) so thin in 1969 that many were broken nearly immediately after laying, so that pesticide residue analyses had to be done on lipids extracted from crushed reminants of some of these fresh eggs. Such eggs would tend to be destroyed before the arrival of egg collectors; their absence in collections would potentially bias reported decreases as too low. This bias is possibly present in our data through 1966; it is present to a lesser extent after about 1966 when eggs were collected more often by ecologists than oologists. Since raptorial birds tend to eat their own broken eggs (reviewed by Ratcliffe, 1970), the bias still tends to be a real one in such species.

RESULTS AND DISCUSSION

Pre-1946 Eggshell Changes

A critically important hypothesis at the start centers on the possibility that significant decreases in eggshell weight and thickness

have in some way been occurring before 1946 or 1947 on a large scale. That this has not taken place in Eurasian Sparrow Hawks (Accipiter nisus) and Peregrine Falcons (Falco peregrinus) in Great Britain for the period 1900 to 1945 was shown by Ratcliffe (1967, 1970) and for Peregrine Falcons in southern California from 1890 to 1945 by Hickey & Anderson (1968) (see Figure 1). Pre-1947 changes were also not evident in Florida Bald Eagles (Haliaeetus leucocephalus), where a 1947 change is suggested from eggshell-weight data (Figure 2). We further tested this hypothesis by examining the shell-thickness indices on a decade by decade basis for 11 species from 14 geographical areas (Table 2). In order to make all observations in these tests independent of one another, we randomly selected single eggs from all clutches. Where recent data were used, these represented both clutches collected by egg collectors and single eggs taken by us or our cooperators in a random fashion from individual nests. We used Ratcliffe's thickness index in this test because of its suitability as a measure of thickness (Table 1). These decade comparisons gave only 1 significant, pre-1940 difference in 91 decade-comparisons (Table 2); Golden Eagle (Aquila chrysaëtos) eggs in 1890-99 (n = 32) were not significantly different from post-1950 eggs of this species. Due to the "rarity" of pre-1939 eggshell changes (the one we report here might even theoretically be due to a sampling error), we believe that our total, pre-1947 samples--all decades combined--are our best representatives for descriptive purposes as well as for comparisons within a given geographical unit. Thus, we feel justified in the comparisons presented below.

Recent Eggshell Changes

Where we made 166 post-1946 eggshell comparisons (Tables 3 to 7, further scientific names will be given there), we found statistically

significant decreases in 103 (62%), nonsignificant changes or no changes in 61 (37%) and significant increases in 2 (1%).

Fish-eating birds.--We found variable, but generally what we considered significant changes in most of the fish-eating species of nonraptorial birds we examined (Table 3). White Pelicans and Common Loons seem to show only more recent changes (1960s) when compared to Brown Pelicans (early 1950s) and Double-crested Cormorants (late 1940s and early 1950s in most cases). Geographical as well as temporal variability associated with post-1947 eggshells is evident from the data on Great Blue Herons and possibly Black-crowned Night Herons. Brown Pelicans, Double-crested Cormorants and Black-crowned Night Herons seem to have suffered the greatest effects of the eggshell thinning syndrome.

The northern population segment of the Brown Pelican along our West Coast is now believed to be "on the brink of disaster" (AOU, 1969). The Gulf Coast population was also considered as "endangered" by the AOU (1968). Risebrough et al. (1970) and Keith et al. (1970) have demonstrated that high levels of p,p'-DDE are present in California Brown Pelicans and that extreme eggshell thinning (-34 to -53%) is associated with such residues. PCBs (polychlorinated biphenyls) are also present. Eggshell thinning in eastern colonies was not as extensive in 1969 (-7.5% in Florida and -16.9% in South Carolina) (Blus, 1970). White Pelicans from interior North America showed DDT-related eggshell thinning of a seemingly minor nature (-4.5%) (Anderson et al., 1969), and this species does not presently appear to be seriously declining in recent decades except for possibly slow, long-term declines associated with habitat encroachment and disturbances (Lies & Behle, 1966). The high level of recent thinning in British Columbia White Pelicans (Table 3) and the presence of highly significant decreases in this species (Table 2), suggest potentially

serious problems with this species in some areas, and we conclude that the White Pelican population deserves a close future watch.

Double-crested Cormorants from interior Wisconsin showed eggshell thinning on the order of -20% and the highest egg levels of DDE compared to other colonies of this species from interior North America in 1965 (Anderson et al., 1969); this population has decreased considerably in recent years (Anderson & Hamerstrom, 1967). Eggshell changes in this species were observed on Lake Michigan as early as 1955 (Table 3). Cormorants are now nearly gone from Lake Superior (Ontario and upper Michigan) (S. Postupalsky, personal communication), where substantial eggshell thinning was observed as early as 1959 (Table 3). These birds likely winter on the Gulf Coast (Lewis, 1929: 20-22) where Brown Pelicans once bred in large numbers. The substantial decreases in eggshell measurements of Black-crowned Night Herons in New Jersey in 1952 (Table 3) have been accompanied by reports of a 90% decline in nearby eastern Long Island, New York, as of 1965 (Peterson, 1969).

Accipiters and Buteos.--Accipitrine hawks tend to have had eggshell changes about twice as great as the buteos we examined (Table 4), unweighted means of the two groups being about 11 and 4 percent, respectively. These phenomena tend to parallel the reported population declines of Cooper's Hawks and Sharp-shinned Hawks in eastern North America (Spofford, 1969), the better numbers of Cooper's Hawks in the West (Peterson, 1969) and the generally stationary numbers of buteos at least in the East (Spofford, 1969)--to which the Red-shouldered Hawk was a puzzling exception. The changes for Goshawks in California (-12%), Red-tailed Hawks in Montana (-14%) and Red-shouldered Hawks in south Texas (-15 to -18%) come as some surprise, and their population significance is unknown at this time. The general conclusions of

Peterson (1969) that bird-eaters are more affected than mammal- or reptile-eaters are sustained by these data, although the eggshell change in Red-shoulder Hawks remains to be explained.

Eagles, Osprey and Marsh Hawk.--Golden Eagles (primarily mammal-eaters), in contrast to Bald Eagles (fish-eaters), showed few changes exceeding 10% throughout the spectrum of our data, excepting a small sample from Alaska in the early 1960s (Table 5). As already noted (Table 2), one pre-1939 decade sample of this species showed a thickness index similiar to and not significantly different from our post-1939 samples. The recent Alaskan sample represented eggshells from two females, and we have reservations on that eggshell change. Our pre-1947 sample from Alaska was small and not significantly different from its temporal equivalent, Golden Eagles from further to the south; nonetheless, we kept it separate on the basis of geographical separation and feel that no ecological conclusions should be drawn until more data are available from Alaska.

Small samples of Marsh Hawk eggshells showed changes in most areas where samples were available, and Ospreys from eastern U.S. (decline summarized by Peterson, 1969) showed the same phenomenon (Table 5). Small samples of Florida Osprey from 1949 and 1960 showed rather substantial eggshell changes, as well. This is in contrast, perhaps, from a population viewpoint, to the Osprey situation in Florida Bay, Florida, where the Osprey was reported as stationary in 1968-69 (Henny & Ogden, 1970).

Falcons.--The eggshell changes we observed for Gyrfalcons were considered statistically significant but were below 10%. We do not know that 10% is a critical level, and it was arbitrarily chosen by us here for discussion purposes. Our Prairie Falcon data exhibited

variable eggshell changes, many of which seem to be of a critical magnitude (Table 6). Changes occurred in southern California where population declines are known (Glading in Hickey, 1969), although we could not statistically demonstrate that these changes were real (Table 2). Changes were evident in New Mexico Prairie Falcons (Table 6), adjacent to Utah where that species has also declined due to various reasons, including some disturbances by falconers (White, 1969). Peregrines showed nearly universal declines in eggshell weight and thickness. The exceptions were one early clutch (1948) from Baja and 1947-53 specimens from British Columbia (Table 6). One normal clutch was also observed from southern California as late as 1952 (Figure 1). The two eggshells taken in 1966 in British Columbia were not tested, but all measurements were below the pre-1947 lower 95% confidence limits. The statistical significance of the eggshell change in Peregrines (Table 2) leaves little doubt as to its recent occurrence. American Sparrow Hawks showed small eggshell changes in our data, the exceptions being two clutches from 1952-63 in eastern U.S. (Table 6). This species possibly shows some "recovery" when very recent specimens are compared to those from the late 1940s and early 1950s (Table 6, data from California and British Columbia).

Areas of low productivity for Prairie Falcons were found in central Canada by Fyfe et al. (1969) to harbor falcons with egg residues of DDE higher than in falcon eggs from areas of more satisfactory productivity. Also associated with the high DDE residues and low productivity were the thinnest eggshells in 1966-68 and a 34% reduction in occupied territories over the ten years prior to their study. The overall mean level of eggshell thinning reported by Fyfe et al. (1969) was -11%. The various local breeding populations they studied tended to have similiar, local

DDE levels but dissimiliar interregional levels, resulting in a generally consistent intraregional pattern of contamination but an interregionally patchy situation. Enderson & Berger (1970) have also established a relationship between chlorinated hydrocarbons, thin eggshells and lowered hatching success in Prairie Falcons from Colorado.

The Peregrine story has already been summarized (Hickey, 1969), and the general syndrome is similiar and better documented with respect to population decreases. Arctic Peregrines now show a progressive eggshell thinning (Table 6) along with high levels of chlorinated hydrocarbons in northern Alaska (Cade et al., 1968), northwest Canada (Enderson & Berger, 1968) and in eastern Arctic Canada (Berger et al., 1970). Apparently, the Peregrine situation is now characterized by eggshell thinning on a continental scale.

Whooping Crane, Herring Gulls, Great Horned Owls and Crows.--Whooping Crane eggshells did not show significant changes in 1967-69 samples from hatched eggs (Anderson & Kreitzer, 1970; Table 7). Herring Gulls on Lake Michigan experienced local, heavy eggshell breakage and reproductive failures in 1964 (Keith, 1966), and subsequent data from that area substantiated that 1964 was a period of extremely high levels of DDE and a period of maximum eggshell thinning, approaching -31% in broken eggs (Anderson et al., 1970b; Herring Gull data summarized in Table 7). Changes were not detected until the early 1950s. Herring Gulls from other areas exhibited lesser magnitudes of eggshell change (Table 7) and lower residues (Hickey & Anderson, 1968).

Two species believed to be currently stationary, the Great Horned Owl and Common Crow, showed generally small changes or no changes at all (Table 7). One local change, in Great Horned Owls from Florida

as early as the late 1940s and early 1950s, exceeded 10%, however. This change is indeed worthy of follow-up research.

Some General Characteristics of Recent Eggshell Changes

The limited post-1947 data in Tables 3 to 7 seem to provide enough material for several generalizations regarding the eggshell-thinning syndrome. First, no increases in eggshell thickness or thickness index that we regarded as significant occurred in any of the eggshells we examined except for Common Crows. We are tempted to cite the work of Jefferies (1969) concerning another passerine, Lonchura striata, where eggshells became thicker-shelled (but smaller) upon DDT treatment. There were no volume differences observed between these two sets of crow data and their pre-1947 measurements, however, and the occurrence of slightly thin eggshells in some specimens of Common Crow (Table 7) suggests to us a sampling error instead.

The changes we encountered seemed to follow four general categories: (1) "ups and downs" within a given geographical area, implying the potential for "recovery", such as that observed with California Sparrow Hawks (Table 6); such occurrences might be similiar to that reported by Lockie et al. (1969) for Scottish Golden Eagles, (2) steady declines of eggshell weights and thicknesses such as those observed with Ontario cormorants (Table 3), (3) early eggshell changes such as those observed with Peregrines in eastern U.S. (Table 6); these were followed by complete extirpation (Berger et al., 1969) so that recent data are not available, and (4) only very recent eggshell changes such as those observed with White Pelicans (Table 3).

The eggshell thinning syndrome seems to be a general phenomenon among many of the species we studied; however, temporal variation ("spottiness") in eggshell thinning is evident after 1947. Some species

did not experience decreases until the 1960s; others began as early as 1947. This seems to be an important characteristic of the phenomenon. In species where eggshell changes have occurred, not all changes correspond to the general environmental introduction of DDT in the mid-1940s, but on the other hand, there is no evidence that DDT was a global pollutant as early as then. In all the species we examined, general eggshell changes were not observed until the post-1940 decades. Eggshell thinning on a widespread basis is a recent phenomenon.

Another seemingly important generalization from the data in Tables 3 to 7 might be the apparent geographical "spottiness" observed. Certain areas and populations show eggshell changes, others do not. Where data were available, a general but loose relationship seems to exist between population status and degree of eggshell change in many cases. Such data are tempting indeed, but we must stress that these associations are purely circumstantial in most cases. Changes in eggshells at least seem generally and partially related to changes in population status--not that all population changes are associated with thin eggshells--but when excessive eggshell changes are observed, say above 15% to 20% for a period of years, the population in question seems to be generally in trouble. In species with significant population reserves of nonbreeding subadults, a sustained reproductive failure will not affect the known nesting population for several years. This occurred in the Peregrine Falcon in the late 1940s and may now be taking place in the California Brown Pelicans.

Ratcliffe (1969) has argued that increased adult mortality--as well as reproductive failure--played an important role in the post-1955 population crash of the Peregrine Falcon in Britain. The excellent census

data on this species provided by Rice (1969) and Herbert & Herbert (1969) for eastern Pennsylvania, New Jersey and southern New York clearly show a population decline far in excess of what one would estimate to be the normal adult mortality rate. The population decline of Ospreys in Connecticut (Ames & Mersereau, 1964; Peterson, 1969) displays the same phenomenon. In other parts of North America, however, known rates of Osprey population decline agree rather well with calculated decreases in net productivity (Henny & Ogden, 1970). It seems highly likely that North American birds are experiencing a spectrum of population effects due to varying degrees of exposure to chemical pollutants. Adult mortality will always be difficult to trace on a population basis. Its occurrence in individual Herring Gulls has been traced to DDT-type compounds by Hickey et al. (1966) and to dieldrin in Bald Eagles by Reichel et al. (1969).

Identification of Pollutants

Up to the present time, the effect of mercury on North American bird populations remains unknown, and the occurrence of this pollutant in the North American environment can only be noted here as generating a tremendous amount of new and potentially interesting research.

The discovery of high levels of PCBs in the natural environment (Jensen, 1966; Widmark, 1967; and others) and their frequent association with DDE in the lipid reservoir of the avian body (Reynolds, 1970) has opened up the possibility that these chemical pollutants may in some way contribute to the eggshell thinning now being found on two continents. Estimated residues of PCBs were found by Anderson et al. (1969) to be inversely correlated with eggshell thickness in Double-crested Cormorants but not in White Pelicans; whereas, DDE levels were correlated with shell thinning in both species. The PCB levels in the pelicans were,

however, relatively low. The field evaluation of PCB effects certainly invites a broader survey. In our own studies of eggshell changes in Herring Gulls, we have concluded that more variation in eggshell thickness could be accounted for by DDE than apparent PCB, but that both seem potentially important at this time (Anderspn et al., 1970b).

The list of factors producing eggshell changes in poultry is a long one (Romanoff & Romanoff, 1949; Sturkie, 1965; Simkiss, 1967). The eggshell changes reported in wild birds by Ratcliffe (1967, 1970) for Britain and by various North American authors have been followed by controlled experiments testing the new hypothesis that these remarkable physiological changes can be produced by various chlorinated hydrocarbons. Porter & Wiemeyer (1969) demonstrated eggshell thinning in American Sparrow Hawks and the associated symptoms of egg disappearance, egg breakage and lowered productivity. These birds were fed a of dieldrin and p,p'-DDT. Heath et al. (1969) demonstrated similiar phenomena with Mallards (Anas platyrhynchos) fed very low levels of p,p'-DDE. Such eggshell thinning was verified by Risebrough et al. (1970) with mallards fed similiar levels of p,p'-DDE. Peakall (1970) induced thin shells in Ringdoves (Streptopelia risoria) injected with p,p'-DDT and p,p'-DDE. Bitman et al. (1969) and Bitman (1970) demonstrated that eggshell thinning was possible in Coturnix coturnix fed high levels of p,p'-DDT and o,p'-DDT. Lehner & Egbert (1969) reported minor eggshell changes in Mallards fed dieldrin; whereas, Dahlgren & Linder (1970) could not produce the same effects in Ring-necked Pheasants (Phasianus colchicus) fed dieldrin. Nor could Peakall (1970) produce eggshell thinning with dieldrin injections in Ringdoves.

The recent shell changes found in wild birds in North America have been associated in 11 cases with DDE or DDT-family residues in the eggs. These residues have ranged from 34 to 2525 ppm on a lipid basis (Table 8); residues of 7 and 30 ppm apparently produced no detectable eggshell changes in two species. Some interspecific differences in response to these environmental contaminants appear to be suggested by the data now available (Table 8).

Pesticides and other compounds in nature are mixtures, each component of a given residue spectrum may have unique physiological effects, and combinations of pollutants may have additional effects not manifested by each singly. The observation of gross physiological end-results in the field are probably in reality a combination of causes, and each ecological situation may be unique.

SUMMARY

Analysis of eggshell thickness-index changes on a decade basis, carried out with 2,088 eggs representing that many individual females of 11 species and 14 geographical areas, disclosed an apparent decrease in Golden Eagles in the 1890s in western North America; this represented 1 significant decade-change (a decrease) out of 91 decades compared. Comparisons in the other 13 analyses disclosed no significant changes. When this comparison was enlarged to include a total of 2,804 eggs through 1969, significant decade differences were apparent in 12 of the 14 cases, 9 of these at the 0.005 level of probability. In this arbitrarily selected group of species, we conclude that eggshell changes were rare before 1939 and common sometime thereafter.

Expansion of this sample to 20,654 eggshells taken prior to 1946 and to 3,004 taken since then reveals that 9 out of 25 species have sustained shell-thickness and shell-weight decreases of 20 or more

percent, at least for brief periods: the Peregrine Falcon in at least three regions, the Marsh Hawk and Brown Pelican in two regions and the Prairie Falcon, Cooper's Hawk, Double-crested Cormorant, Black-crowned Night Heron, Bald Eagle and Osprey in at least one region each. In eight of these, regional declines are known; and in some cases, these declines continue.

These eggshell changes appear to be absent in Whooping Cranes, Broad-winged Hawks and Rough-legged Hawks. They have reached 15-19% in Ontario Common Loons, 14-16% in some White Pelicans, 7-9% in some Great Blue Herons, 8-12% in California Goshawks, 9-13% in some Sharp-shinned Hawks and 10% in Great Lakes Herring Gulls. Changes generally under 10% (with some local exceptions) were observed in Red-tailed Hawks, Red-shouldered Hawks, Golden Eagles, Gyrfalcons, American Sparrow Hawks, Great Horned Owls and Common Crows. The species we reviewed are not regarded as a representative cross-section of North American birdlife, and the population significances of the data are restricted by small samples and time spans, often representing only a few years in a given region.

The shell-change data seem to characterize regional differences in chemical fallout, contamination that varies with diet and phylogenetic differences in sensitivity to pollutants. DDE is the pollutant most often associated with these physiological changes and population decreases. The importance of additional chlorinated hydrocarbons, including PCBs, as well as mercury remains to be worked out. The threat to North American species is geographically widespread and not limited to the site of pesticide application. It probably involves a small

fraction of the continent's species and often only some geographic fraction of a species population; but it seems to be mounting, and its occurrence in the tropical parts of North and South America remains to be worked out.

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Figure 1. Raw eggshell-weight data plotted against time for California Peregrines. These data suggest an eggshell change in 1947.

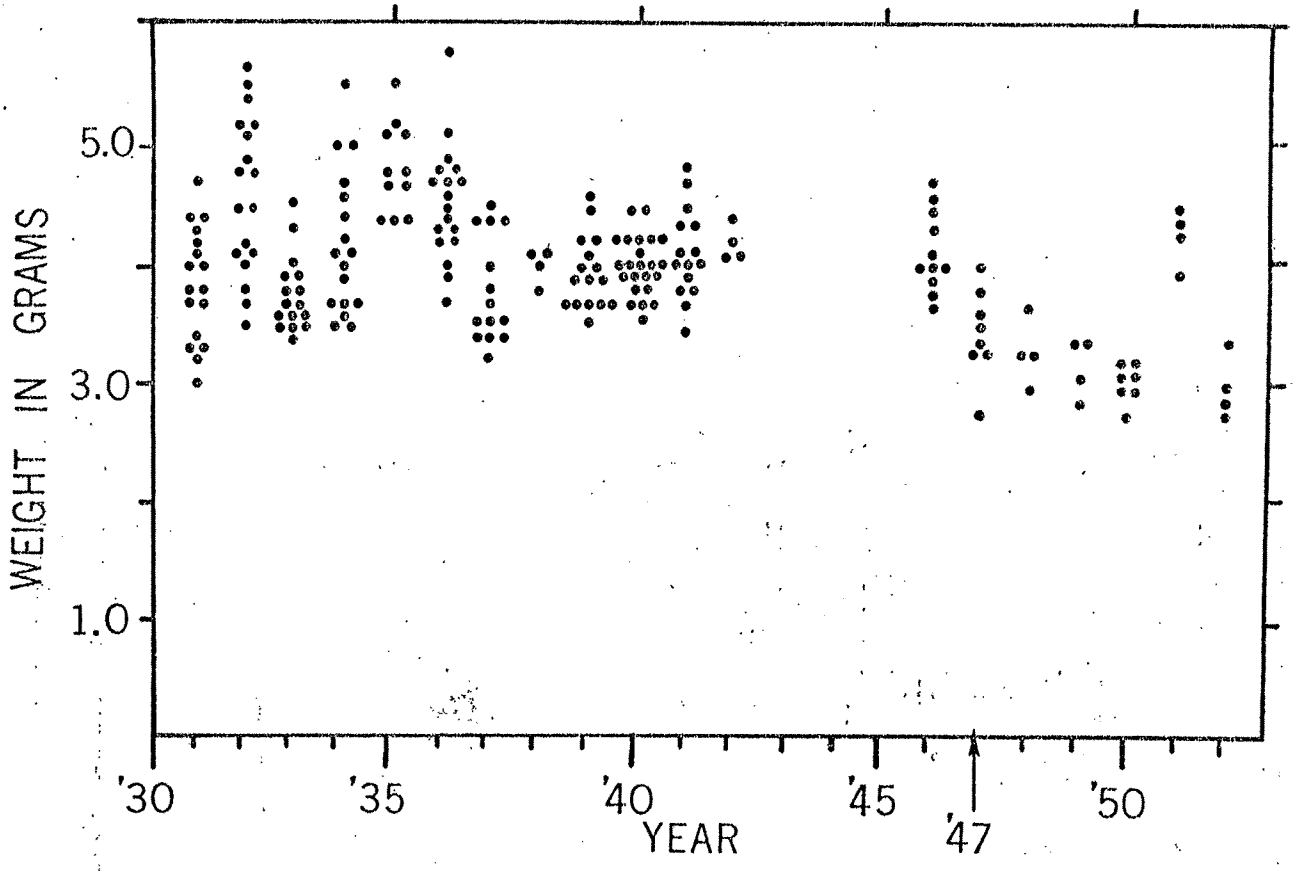

Figure 2. Eggshell weight versus time in Florida Bald Eagles, again suggesting a general change beginning in 1947. The 1969 data (A. Sprunt IV, personal communication) suggest some "recovery" or represent a series of females less affected than previously.

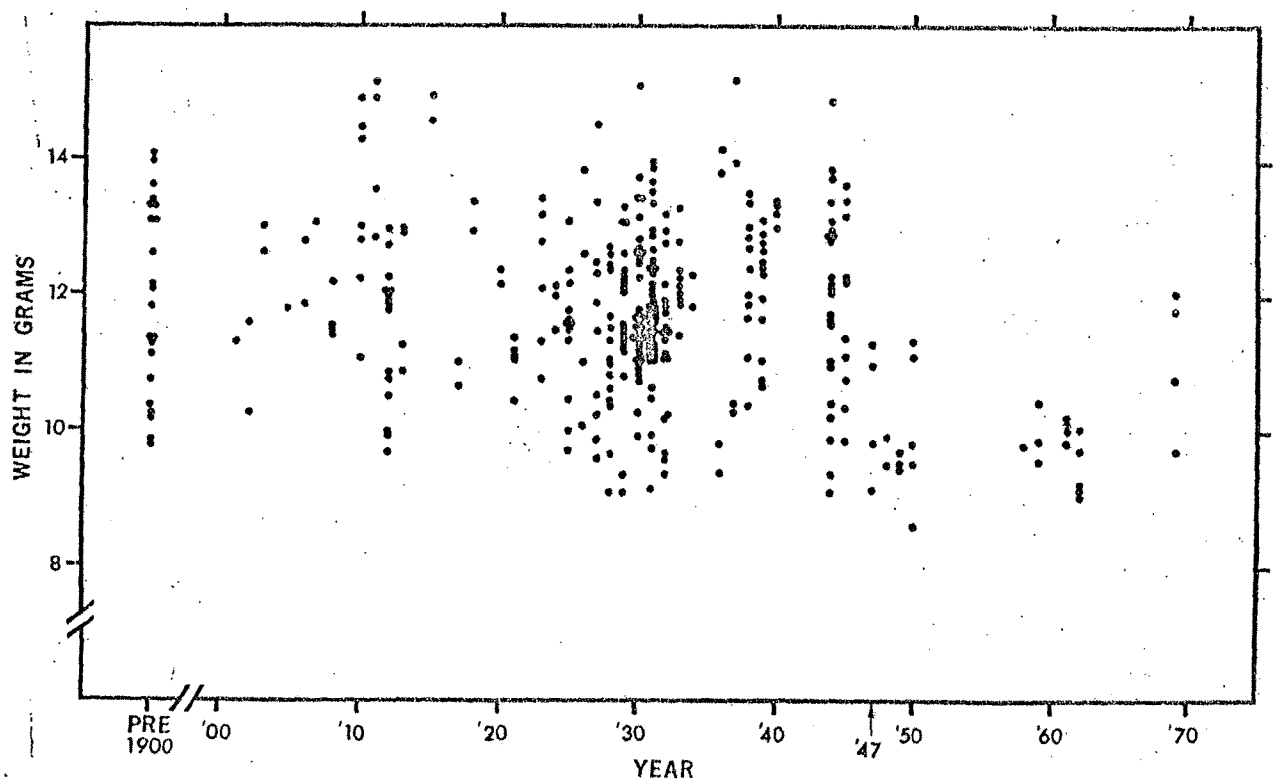

Table 1. Relationship between Ratcliffe's (1967) thickness index and measured eggshell thickness in nine species.

Species	Correlation coefficient[1]	Regression equation ($\hat{Y} = \alpha + bX$)	Std. err. of slope	F-value[2]
Pelecanus erythrorhynchos	0.842	0.277 + 4.481X	0.290	238.7
Phalacrocorax auritus	0.850	0.264 + 4.342X	0.272	255.5
Nycticorax nycticorax	0.855	-0.025 + 5.025X	0.308	266.7
Aquila chrysaetos	0.878	0.860 + 3.782X	0.208	330.4
Pandion haliaetus	0.918	-0.018 + 5.096X	0.223	521.7
Falco mexicanus	0.675	1.547 + 1.003X	0.111	81.8
Falco sparverius	0.866	0.004 + 5.035X	0.294	294.1
Larus argentatus (Midwest)	0.881	0.052 + 4.470X	0.243	339.1
Larus argentatus (Eastern)	0.904	-0.434 + 5.851X	0.280	437.3
Corvus brachyrhynchos	0.711	0.248 + 3.478X	0.347	100.5

1/ These represent 100 randomly selected eggshells from each species, the correlation coefficient (r) at $P_{.001} = 0.324$.

2/ F-test from Steel & Torrie (1960: 287-289), F-value at $P_{.005} = 8.29$.

Table 2. Decade differences in shell thickness index for selected species.

Species Geographical Area	No. Decades Studied[1]	No. Eggs Used[2]	Decade Differences (F-values) To 1939	Significance[3]	To 1969	Significance[3]
Pelecanus erythrorhynchos						
Interior, n.w. No. Amer.	7(10)	76(189)	0.85	n.s.	7.95	***
Phalacrocorax auritus						
Interior No. Amer.	7(10)	88(131)	1.98	n.s.	4.21	***
Nycticorax nycticorax						
Eastern U. S.	7(10)	116(128)	1.54	n.s.	1.80	n.s.
Aquila chrysaëtos						
Western No. Amer.	7(10)	342(493)	2.98	**	3.08	***
Haliaeetus leucocephalus						
Florida	6(9)	148(183)	1.22	n.s.	7.18	***
Circus cyaneus						
Interior No. Amer.	6(9)	99(110)	1.69	n.s.	4.88	***
Pandion haliaetus						
Eastern U. S.	7(9)	289(294)	1.72	n.s.	3.99	***

Table 2 continued.

Table 2 continued.

Species Geographical Area	No. Decades Studied[1]	No. Eggs Used[2]	Decade Differences (F-values) To 1939	Significance[3]	To 1969	Significance[3]
Falco mexicanus						
Western Scrub Desert	6(8)	200(248)	0.62	n.s.	0.75	n.s.
Falco peregrinus						
California	6(8)	142(152)	1.38	n.s.	7.04	***
Alaska	5(6)	14(15)	1.66	n.s.	5.14	**
Interior Tundra	6(7)	13(35)	0.97	n.s.	2.74	*
Falco sparverius						
Interior No. Amer.	7(10)	238(261)	0.37	n.s.	1.91	*
Larus argentatus						
Atlantic Coast	7(9)	166(211)	1.65	n.s.	3.39	***
Great Lakes	7(10)	157(354)	0.77	n.s.	15.36	***

1/ In parentheses: the total number of decades through 1969 for which data were available.

2/ The total number of variates available through 1939 (in parentheses, through

Table 2 continued.

1969). Only one egg (selected at random) was used from each clutch.

3/ Significant F-values, indicating that at least one decade differed in a series, are marked as follows:

*	$P<0.05$	***	$P<0.005$
**	$P<0.01$	n.s.	not significant

TABLE 3. Eggshell data from North American museums and private egg collections, showing general changes in certain species that are predominantly fish-eaters: Gaviiformes, Pelecaniformes, Ciconiiformes.[1/]

Family[2/] Species, Subspecies (Foods[3/]) Region Involved	Period	Sample Size[4/]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5/]
GAVIIDAE					
Gavia immer (6,4,2,), Common Loon[6/]					
Ontario, Quebec	pre-'47	69(60)	16.14±0.48	0.634±0.013	3.17±0.08
Ontario	1961-69	32(32)	13.13±0.51	0.556±0.014	2.68±0.09
			-19%	-12%	-15%
Alberta Manitoba	pre-'47	70(42)	14.29±0.28	0.602±0.010	3.00±0.04
Alberta	1947-58	8(2)	15.46±0.58	0.615±0.064	3.14±0.11
			--	NS	NS
PELECANIDAE					
Pelecanus erythrorhynchos (6,4), White Pelican					
Western U. S.	pre-'47	268(102)	15.70±0.21	0.676±0.010	3.26±0.03

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Nevada	1968	25(25)	14.24±0.75	0.619±0.022	2.87±0.12
			-9%	-8%	-12%
Pacific Northwest	pre-'47	88(52)	16.47±0.37	0.685±0.012	3.32±0.06
No. California	1947-49	10(4)	14.74±0.96	0.643±0.069	3.15±0.14
			--	NS	NS
No. California	1968	47(47)	14.69±0.53	0.627±0.015	2.99±0.10
			-11%	-8%	-10%
British Columbia	1964-68	13(11)	13.83±1.30	0.597±0.035	2.86±0.25
			-16%	-13%	-14%
Interior No. America	pre-'47	94(92)	16.56±0.30	0.683±0.010	3.33±0.05
Saskatchewan	1949	5(5)	16.79±3.78	0.706±0.077	3.45±0.39
			NS	NS	NS
Manitoba	1952	7(7)	15.6 ±0.87	0.654±0.026	3.20±0.10

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			NS	NS	NS
Alta., Man., Sask., N.D.	1965-68	34(65)	14.99±0.86	0.647±0.026	3.07±0.19
			-9%	-5%	-8%
Pelecanus occidentalis (6), Brown Pelican[6]					
P. o. carolinensis					
Florida, Ga.	pre-'47	208(172)	9.78±0.12	0.557±0.004	2.60±0.02
Florida	1950-53	9(0)	8.10±0.14	no data	2.22±0.09
			-17%	--	-15%
Texas	pre-'47	115(43)	10.00±0.26	0.557±0.012	2.59±0.04
Texas	1951	6(0)	7.96±0.60	no data	2.12±0.10
			-20%	—	-18%
P. o. californicus					
So. California	pre-'47	85(28)	10.59±0.24	0.579±0.014	2.71±0.04
So. California	1962	9(9)	7.89±0.66	0.424±0.018	2.02±0.12

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-26%	-27%	-25%
PHALACROCORACIDAE					
Phalacrocorax auritus (6,4,2), Double-crested cormorant					
P. a. albociliatus					
So. Calif., No. Baja	pre-'47	134(29)	4.70±0.08	0.428±0.012	2.08±0.03
So. California	1949	25(0)	4.64±0.14	no data	1.94±0.05
			-1%	--	-7%
P. a. auritus					
Interior No. America	pre-'47	370(350)	5.04±0.05	0.430±0.003	2.12±0.02
Manitoba	1952	11(11)	4.60±0.27	0.406±0.015	1.98±0.08
			-9%	-6%	-7%
Sask., Man., Mont., N.D., Minn.	1965-67	35(76)	4.53±0.28	0.399±0.014	1.91±0.10
			-10%	-7%	-10%

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Illinois	1948	9(0)	4.70±0.17	no data	2.05±0.06
			-7%	--	-3%
Wisconsin	1955	20(0)	4.33±0.16	no data	1.91±0.07
			-14%	--	-10%
Wisconsin, Michigan	1965-68	5(28)	4.05±0.30	0.309±0.010	1.63±0.04
			-20%	-28%	-23%
Ontario	1947	6(6)	5.22±0.34	0.440±0.013	2.29±0.07
			NS	NS	NS
Ontario	1959-61	7(7)	3.61±0.28	0.340±0.015	1.55±0.06
			-23%	-21%	-27%
Ontario	1969	25(39)	4.07±0.40	0.340±0.020	1.67±0.14
			-19%	-21%	-21%
P. a. floridanus					

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Florida	pre-'47	194(126)	4.45±0.07	0.398±0.004	1.96±0.02
Florida	1947	7(0)	4.88±0.39	no data	2.09±0.11
			NS	--	NS
Florida	1953	8(0)	4.53±0.26	no data	1.89±0.05
			NS	--	NS
Florida	1960	6(0)	4.51±0.33	no data	1.82±0.05
			+1%	--	-7%
ARDEIDAE					
Ardea herodias (6,2,4,5), Great Blue Heron					
A. h. herodias					
So. Canada	pre-'47	217(130)	5.93±0.06	0.393±0.004	2.05±0.02
Ontario	1957-62	24(4)	5.52±0.24	0.370±0.022	1.86±0.07
			-7%	-6%	-9%

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
A. h. treganzi					
Mid-central U. S.	pre-'47	332(202)	6.28±0.06	0.404±0.003	2.11±0.02
Utah	1948-61	35(0)	6.05±0.15	no data	2.02±0.05
			-4%	--	-4%
A. h. fannini					
Pacific Northwest	pre-'47	130(64)	6.10±0.08	0.389±0.005	2.02±0.02
Wash., Br. Col.	1956-59	9(4)	5.75±0.40	0.390±0.005	1.83±0.09
			-6%	0%	-9%
A. h. hyperonca					
So. Calif., Baja	pre-'47	153(53)	5.70±0.10	0.384±0.008	1.99±0.03
So. California	1948-55	22(0)	5.87±0.31	no data	1.95±0.08
			NS	--	NS
A. h. wardi					

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Gulf Coastal Plain	pre-'47	148(81)	6.31±0.10	0.400±0.005	2.05±0.02
Florida	1950-60	17(0)	6.18±0.39	no data	1.98±0.10
			NS	--	NS
Nycticorax nycticorax (6,2,4,5), Black-crowned Night Heron					
N. h. hoactli					
East-central U. S.	pre-'47	335(199)	2.82±0.03	0.289±0.003	1.42±0.01
New Jersey	1952	8(0)	2.21±0.10	no data	1.17±0.05
			-22%	--	-18%
Great Lakes Area	pre-'47	158(134)	2.83±0.04	0.287±0.003	1.44±0.02
Ontario	1959	12(0)	2.71±0.18	no data	1.41±0.06
			NS	--	NS
Ontario	1960-61	25(4)	2.62±0.10	0.285±0.020	1.39±0.04
			-7%	-1%	-3%

TABLE 3 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Ontario	1963-64	12(7)	2.53±0.20 -18%	0.247±0.014 -14%	1.32±0.07 -8%

[1]Only changes significant at the 95% level in at least two of three, or one of two parameters are reported. Significant differences were considered as nonoverlap of 95% C.L.'s, or if close, by t-test. NS=not significant, if series of parameters were NS, no changes were reported.

[2]After AOU Check-list (1957); subspecies and range descriptions are from that source.

[3]Mostly generalized from Martin et al (1951) and Palmer (1962): 1=herbivorous, 2=insectivorous and eating invertebrates, 3=omnivorous, 4=eating cold-blooded vertebrates other than fish, 5=eating mammals, 6=piscivorous, 7=eating birds.

[4]Values in parentheses are sample sizes for thickness only.

[5]After Ratcliffe (1967, 1970).

[6]Summarized from the following references, if already published, in the same sequence as footnoted: H. G. Lumsden (personal communication), Anderson and Hickey (1970).

TABLE 4. Eggshell data from North American museums and private egg collections, showing general changes in certain species of raptors with variable food-habits: Accipitridae (Accipiter, Buteo).[1/]

Family[2/] Species, Subspecies (Foods[3/]) Region Involved	Period	Sample Size[4/]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5/]
ACCIPITRIDAE					
Accipiter gentilis (5,7), Goshawk					
A. g. atricapillus					
California	pre-'47	23(3)	5.96±0.21	0.410±0.025	2.23±0.07
California	1947-64	34(9)	5.22±0.13	0.404±0.027	2.06±0.04
			-12%	-1%	-8%
A. striatus (7,5), Sharp-shinned Hawk					
A. S. velox					
So. Canada	pre-'47	568(197)	1.48±0.02	0.268±0.004	1.31±0.01
Alta., Que.	1947-58	9(4)	1.35±0.08	0.245±0.020	1.14±0.09
			-9%	-8%	-13%
A. cooperi (7,5), Cooper's Hawk					

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Amer. Southwest	pre-'47	302(88)	3.13±0.03	0.336±0.006	1.75±0.02
So. California	1947-48	23(0)	3.16±0.13	no data	1.72±0.06
			NS	--	NS
So. California	1949-50	19(0)	3.14±0.08	no data	1.73±0.03
			NS	--	NS
So. California	1951-52	23(0)	2.80±0.15	no data	1.64±0.09
			-11%	--	-6%
So. California	1956-59	21(0)	2.86±0.17	no data	1.64±0.07
			-9%	--	-6%
New Mexico, Utah	1952-56	24(4)	3.07±0.14	0.335±0.009	1.65±0.05
			NS	NS	--
Arizona	1955	3(0)	3.02±0.68	no data	1.74±0.31
			NS	--	NS

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Manitoba, Br. Col.	pre-'47	44(40)	3.24±0.09	0.348±0.006	1.80±0.04
Alberta, Br. Col.	1949-50	8(0)	2.65±0.14	no data	1.55±0.08
			-18%	--	-14%
Alberta, Br. Col.	1963	6(0)	2.53±0.51	no data	1.44±0.21
			-22%	--	-20%
South Texas	pre-'47	40(4)	3.12±0.15	0.355±0.028	1.79±0.04
South Texas	1949	4(0)	2.94±0.19	no data	1.67±0.07
			-6%	--	-7%
South Texas	1961	4(0)	2.64±0.36	no data	1.52±0.17
			-15%	--	-15%
So. Appalacians	pre-'47	73(21)	3.40±0.06	0.367±0.008	1.84±0.02
So. Car., Tenn.	1947-50	15(5)	2.97±0.10	0.324±0.011	1.61±0.07
			-18%	-12%	-13%

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
So. Car., Tenn.	1958	7(0)	2.84±0.11	no data	1.60±0.09
			-16%	--	-13%
Buteo jamaicensis (5,7,4), Red-tailed Hawk					
B. j. calurus					
California	pre-'47	629(187)	6.32±0.05	0.428±0.004	2.25±0.01
So. Calif.	1950-59	74(2)	5.99±0.14	0.405±0.191	2.13±0.04
			-5%	-5%	-5%
So. Calif.	1960-67	6(0)	5.92±0.73	no data	2.11±0.18
			-6%	--	-6%
Amer. Southwest	pre-'47	191(80)	5.86±0.10	0.406±0.008	2.14±0.03
New Mexico	1951-66	19(0)	5.52±0.21	no data	2.06±0.07
			-6%	--	-4%
No. Prairies[6]	pre-'47	242(186)	6.22±0.08	0.42±0.004	2.23±0.02

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Alberta 1947-58	1947-58	6(3)	6.26±0.57	0.383±0.014	2.19±0.16
			NS	--	NS
Oregon	1950-52	5(0)	6.11±0.65	no data	2.20±0.06
			NS	--	NS
Wyoming, Colorado	1951	8(0)	5.66±0.31	no data	2.06±0.10
			-9%	--	-8%
Montana[7]	1967	4(4)	5.38±0.11	0.385±0.016	1.92±0.15
			-14%	-9%	-14%
B. j. borealis					
Great Lakes Area	pre-'47	517(394)	6.50±0.06	0.433±0.003	2.29±0.02
Ontario	1949-68	23(5)	6.29±0.29	0.422±0.018	2.24±0.05
			NS	NS	NS
B. j. fuertesi					

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
South Texas	pre-'47	115(32)	6.55±0.12	0.432±0.012	2.29±0.03
South Texas	1948-67	39(0)	6.20±0.22	no data	2.17±0.04
			-5%	--	-5%
B. j. umbrinus					
Florida	pre-'47	76(31)	6.31±0.15	0.423±0.012	2.24±0.04
Florida	1949-67	80(0)	6.20±0.25	no data	2.17±0.06
			-2%	--	-3%
Buteo lineatus (5,7,4), Red-shouldered Hawk					
B. l. elegans					
Western U. S.	pre-'47	384(61)	4.16±0.04	0.367±0.005	1.84±0.01
So. California	1947-49	18(0)	4.05±0.42	no data	1.78±0.19
			NS	--	NS
So. California	1950-55	61(0)	4.16±0.11	no data	1.85±0.04

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			NS	--	NS
So. California	1956-60	17(0)	3.63±0.19	no data	1.64±0.05
			-13%	--	-11%
So. California	1961-67	34(0)	4.02±0.15	no data	1.74±0.05
			-3%	--	-5%
B. l. lineatus					
New England to Gt. Lakes	pre-'47	1,170(759)	4.52±0.02	0.364±0.002	1.90±0.01
Ontario, Quebec	1949-53	19(9)	4.35±0.14	0.347±0.021	1.83±0.06
			-4%	-5%	-4%
Ontario, Quebec	1960-68	11(0)	4.37±0.27	no data	1.73±0.10
			-3%	--	-9%
B. l. alleni					
Gulf Coast, Piedmont	pre-'47	300(98)	4.22±0.05	0.353±0.004	1.84±0.02

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
South Carolina	1948-49	9(0)	4.00±0.15	no data	1.83±0.04
			-5%	--	-1%
South Carolina	1952	10(0)	3.80±0.28	no data	1.72±0.09
			-10%	--	-6%
Florida	1947-49	17(0)	4.19±0.22	no data	1.78±0.06
			NS	--	NS
Florida	1950-59	54(0)	4.10±0.10	no data	1.77±0.04
			-3%	--	-4%
Florida	1960-68	49(0)	4.11±0.17	no data	1.79±0.05
			NS	--	NS
B. l. texanus					
South Texas	pre-'47	58(5)	4.34±0.12	0.372±0.020	1.86±0.03
South Texas	1949-51	44(6)	3.69±0.12	no data	1.70±0.05

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-15%	--	-9%
South Texas	1952-54	93(0)	4.06±0.08	no data	1.78±0.03
			-6%	--	-4%
South Texas	1955-60	14(2)	3.54±0.25	0.285±0.063	1.61±0.10
			-18%	-23%	-13%
Buteo platypterus platypterus (2,4,5), Broad-winged Hawk					
Interior No. America	pre-'47	316(250)	3.29±0.06	0.330±0.004	1.70±0.02
Man., Wisc., Mich.	1947-56	10(0)	3.49±0.16	no data	1.74±0.08
			NS	--	NS
Buteo lagopus (5,7), Rough-legged Hawk					
Arctic No. America	pre-'47	215(172)	5.60±0.07	0.418±0.004	2.20±0.02
Ungava, N.W.T.	1961-66	7(7)	5.42±0.48	0.430±0.011	2.25±0.13
			NS	NS	NS

TABLE 4 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Ungava, N.W.T.	1967-68	9(9)	5.79±0.43	0.432±0.20	2.31±0.15
			NS	NS	—

[1] All footnotes follow those of Table 1, excepting footnotes 6 and 7.

[6] Extensive intergradation of adjoining subspecies with B. j. krideri (AOU Check-list, 1957) prevented us from further taxonomic separation.

[7] From Seidensticker and Reynolds (1970).

TABLE 5. Eggshell data from North American Museums and private egg collections, showing general changes in certain species of raptors with variable food-habits: Accipitridae (eagles, Marsh Hawk), Pandionidae.[1/]

Family[2/] Species, Subspecies (Foods[3/]) Region Involved	Period	Sample Size[4/]	Means ± 95% C.L.'s, Changes Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5/]
Aquila chrysaetos canadensis (5,7), Golden eagle					
Western No. America	pre-'47	824(290)	13.22±0.10	0.583±0.006	3.03±0.02
California	1947	12(0)	13.24±1.12	no data	3.05±0.19
			NS	—	NS
California	1948	12(4)	12.41±1.11	0.598±0.051	2.95±0.23
			NS	NS	NS
California	1949	12(8)	12.80±0.65	0.555±0.033	2.86±0.12
			NS	NS	—
California	1950-52	10(0)	12.99±0.62	no data	2.91±0.13
			NS	—	NS
California	1953-55	22(3)	12.00±0.49	0.510±0.124	2.76±0.09

TABLE 5 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-9%	-13%	-9%
California	1956-59	16(0)	12.82±0.66	no data	2.95±0.11
			NS	--	NS
California	1960-63	17(0)	12.27±0.76	no data	2.69±0.14
			-7%	--	-11%
California	1964-65	9(2)	14.33±0.91	0.605±0.064	3.13±0.14
			--	NS	NS
New Mexico	1951-55	21(0)	14.26±0.68	no data	3.07±0.09
			--	--	NS
New Mexico	1956-59	18(0)	12.98±0.75	no data	3.04±0.13
			NS	--	NS
New Mexico	1960-61	12(0)	12.31±0.68	no data	2.89±0.11
			-7%	--	-5%

TABLE 5 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Utah	1949-69	17(4)	13.52±0.78	0.623±0.057	3.10±0.14
			NS	NS	NS
Arizona	1953-58	17(0)	12.17±0.76	no data	2.84±0.14
			-10%	--	-8%
Arizona	1961-62	4(0)	12.67±0.37	no data	2.96±0.18
			-6%	--	-5%
Montana[6]	1967	7(7)	13.42±1.70	0.637±0.030	3.13±0.21
			NS	--	NS
Alaska	pre-'47	11(7)	14.38±1.34	0.623±0.057	3.32±0.20
Alaska	1962-64	4(4)	11.82±0.80	0.580±0.039	2.98±0.10
			-18%	-7%	-4%

Haliaeetus leucocephalus (6,7,5), Bald eagle

H. l. leucocephalus

TABLE 5 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Florida	pre-'47	337(211)	11.93±0.14	0.584±0.007	3.10±0.03
Florida	1944-45	28(0)	11.62±0.65	no data	2.98±0.10
			NS	--	NS
Florida	1947-48	6(0)	10.09±0.88	no data	2.62±0.16
			-15%	--	-15%
Florida	1949-50	9(3)	9.86±0.66	0.487±0.057	2.50±0.13
			-17%	-17%	-19%
Florida	1958-59	4(0)	9.89±0.58	no data	2.43±0.07
			-17%	--	-22%
Florida	1961-62	8(0)	9.67±0.39	no data	2.56±0.06
			-19%	--	-17%
Texas, Louisiana	pre-'47	29(19)	12.54±0.57	0.603±0.024	3.15±0.10
South Texas 1947-49	1947-49	12(0)	12.08±0.64	no data	3.03±0.11

TABLE 5 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			NS	--	NS
South Texas	1950-52	6(0)	11.05±0.39	no data	2.19±0.13
			-12%	--	-30%
Circus cyaneus hudsonius (5,4,7), Marsh Hawk					
Western U. S.	pre-'47	278(91)	2.69±0.08	0.319±0.008	1.60±0.02
California	1950-52	10(0)	2.35±0.09	no data	1.36±0.05
			-13%	--	-15%
Oregon	1958-60	7(0)	2.03±0.07	no data	1.22±0.04
			-25%	--	24%
Eastern, Interior N. Am.	pre-'47	547(349)	2.61±0.04	0.319±0.002	1.59±0.01
Alberta	1947-52	9(0)	2.34±0.20	no data	1.52±0.06
			-10%	--	-4%
Alberta	1956-57	12(0)	1.99±0.10	no data	1.20±0.08

TABLE 5 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-24%	--	-24%
Br. Col.	1961	5(0)	2.12±0.22	no data	1.31±0.08
			-19%	--	-18%
New Jersey	1947	5(0)	2.51±0.18	0.316±0.023	1.54±0.14
			NS	NS	NS
Ontario	1967	5(0)	2.63±0.13	no data	1.45±0.05
			0%	--	-9%
Wisconsin	1959	8(0)	2.27±0.22	no data	1.37±0.08
			-13%	--	-14%
PANDIONIDAE					
Pandion haliaetus carolinensis (6), Osprey					
Florida	pre-'47	83(46)	7.16±0.13	0.498±0.009	2.53±0.04
Florida	1949	3(0)	6.33±0.49	no data	2.13±0.14

TABLE 5 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-12%	--	-16%
Florida	1960	6(0)	6.20±0.31	no data	2.20±0.17
			-13%	--	-13%
Eastern U. S.	pre-'47	963(365)	7.07±0.04	0.505±0.004	2.57±0.01
Md., N. J., Conn.	1957	10(4)	5.81±0.92	0.398±0.035	2.03±0.25
			-18%	-21%	-21%

[1] All footnotes follow those of Table 1, excepting footnote 6.

[2] From Seidensticker and Reynolds (1970).

TABLE 6. Eggshell data from North American museums and private egg collections, showing general changes in certain species of falcons which are variable in food-habits: Falconidae.[1/]

Family[2/] Species, Subspecies (Foods[3/]) Region Involved	Period	Sample Size[4/]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5/]
FALCONIDAE					
Falco rusticolus obsoletus (7,5), GyrFalcon					
Arctic No. Am., Greenland	pre-'47	59(39)	6.24±0.17	0.432±0.010	2.29±0.04
Alaska, N.W.T.	1958-67	7(2)	5.70±0.33	0.410±0.000	2.21±0.09
			-9%	-5%	-3%
Falco mexicanus (5,7), Prairie Falcon					
West. U. S. (scrub desert)	pre-'47	1,130(150)	3.98±0.02	0.365±0.003	1.90±0.01
So. California	1948-51	24(0)	3.52±0.10	no data	1.65±0.06
			-12%	--	-13%
So. California	1952-57	18(0)	3.31±0.13	no data	1.52±0.18
			-17%	--	-20%
West. U. S. (West. grassland)	pre-'47	243(38)	4.15±0.04	0.374±0.008	1.94±0.02

TABLE 6 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Oregon	1947-53	15(0)	3.86±0.09	no data	1.83±0.04
			-7%	--	-6%
West. N. Am. (North grassland)[6]	pre-'47	226(167)	4.15±0.05	0.366±0.003	1.92±0.02
Wyoming	1951	8(0)	3.71±0.28	no data	1.72±0.10
			-11%	--	-10%
Alberta	1954	5(5)	3.98±0.36	0.366±0.026	1.99±0.22
			NS	NS	NS
Alberta, Montana	1965-67	17(12)	3.88±0.14	0.354±0.016	1.80±0.07
			-4%	-3%	-6%
Saskatchewan	1965-67	7(7)	3.42±0.44	0.320±0.032	1.62±0.17
			-18%	-13%	-16%
Am. S.W. (So. grassland)	pre-'47	80(46)	3.94±0.08	0.359±0.004	1.89±0.02
New Mexico	1951	3(3)	3.10±0.23	0.307±0.029	1.50±0.13

TABLE 6 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-21%	-14%	-21%
New Mexico	1965	5(0)	2.83±0.15	no data	1.36±0.06
			-28%	--	-28%
Falco peregrinus (7), Peregrine Falcon					
F. p. tundrius[7]					
Arctic, subarctic Alaska	pre-'47	71(53)	4.09±0.09	0.360±0.007	1.86±0.04
Alaska	1952-57	10(8)	3.23±0.15	0.293±0.018	1.50±0.05
			-21%	-19%	-19%
Alaska	1964	3(3)	3.11±0.25	0.277±0.014	1.42±0.04
			-24%	-23%	-24%
Interior Arctic No. Amer.	pre-'47	59(40)	3.93±0.09	0.368±0.006	1.88±0.03
Ungava, N.W.T.	1947-57	7(3)	3.67±0.14	0.343±0.038	1.60±0.14
			-7%	-7%	-15%

TABLE 6 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Ungava, N.W.T.[6]	1966-69	23(26)	3.55±0.40	0.315±0.019	1.59±0.11
			-10%	-14%	-15%
F. p. pealei					
Canadian West Coast	pre-'47	91(58)	4.22±0.07	0.363±0.005	1.91±0.02
British Columbia	1947-53	24(7)	4.22±0.12	0.366±0.031	1.90±0.06
			NS	NS	NS
British Columbia	1966	2(2)	3.67	0.320	1.79
			-13%	-12%	-6%
F. p. anatum					
So. California	pre-'47	586(229)	4.25±0.04	0.365±0.003	1.94±0.01
So. California	1947-48	12(4)	3.45±0.22	0.335±0.042	1.59±0.09
			-19%	-3%	-18%
So. California	1949-50	11(0)	3.14±0.14	no data	1.43±0.05

TABLE 6 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-26%	--	-26%
So. California[8]	1951-52	8(2)	3.70±0.58	0.295±0.064	1.74±0.23
			-13%	-19%	-10%
Alta., Sask., Mont.	pre-'47	79(71)	4.12±0.09	0.359±0.005	1.87±0.03
Alberta	1952-54	13(13)	3.86±0.17	0.331±0.009	1.71±0.08
			-6%	-8%	-8%
Baja	pre-'47	105(46)	3.96±0.08	0.348±0.006	1.81±0.03
Baja	1948	4(0)	3.72±0.34	no data	1.74±0.16
			NS	--	NS
Eastern U. S.	pre-'47	392(94)	4.47±0.04	0.375±0.005	1.99±0.01
Mass., N. J.	1947-50	6(3)	3.35±0.20	0.310±0.025	1.54±0.09
			-25%	-17%	-23%

Falco sparverius (2,5,7), Sparrow Hawk

TABLE 6 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Interior - Northern N. Amer.	pre-'47	1,251(583)	1.05±0.01	0.211±0.001	1.06±0.004
Alta., Man., Ont.	1948-58	17(0)	1.05±0.06	no data	1.05±0.06
			NS	--	NS
Wash., No. Calif.	1947	11(6)	1.04±0.05	0.203±0.009	1.06±0.06
			NS	NS	NS
Br. Col., No. Calif.	1951-53	14(0)	0.96±0.07	no data	0.98±0.07
			-8%	--	-8%
Br. Col., No. Calif.	1958-61	13(10)	1.02±0.04	0.220±0.003	1.04±0.03
			NS	--	NS
New York, Indiana	1952-63	8(8)	0.91±0.09	0.181±0.016	0.93±0.12
			-13%	-14%	-12%
Tennessee	1952-58	8(0)	0.93±0.08	no data	0.95±0.08
			-11%	--	-10%

TABLE 6 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Am. S. W. (desert, dry)	pre-'47	972(49)	1.03±0.01	0.219±0.005	1.05±0.004
Arizona, New Mexico	1955-58	11(0)	1.01±0.09	no data	1.07±0.04
			NS	--	NS
New Mexico	1965-67	21(0)	0.99±0.05	no data	1.02±0.04
			NS	--	NS
So. California	1947-49	14(0)	0.97±0.04	no data	1.00±0.04
			-6%	--	-5%
So. California	1953-59	27(0)	1.03±0.03	no data	1.05±0.05
			NS	--	NS
F. s. paulus					
Florida	pre-'47	860(53)	0.96±0.01	0.208±0.005	1.02±0.01
Florida	1950-59	26(0)	0.95±0.06	no data	1.01±0.04
			NS	--	NS

TABLE 6 Continued.

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[1]All footnotes follow those of Table 1, excepting footnotes 6, 7, and 8.

[6]Partly from Fyfe et al (1969) and Berger et al (1970).

[7]F. p. tundrius is after White (1968).

[8]Included a "normal" set from the interior (Figure 2).

TABLE 7. Eggshell data from North American museums and private egg collections, showing general changes in certain representative species from various orders: Gruiformes, Charadriiformes, Strigiformes, Passeriformes.[1]

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
GRUIDAE					
Grus americana (1,2,4), Whooping Crane[6]					
Interior No. America	pre-'47	52(52)	20.07±0.63	0.604±0.014	3.23±0.08
Northwest Territories	1967-69	0(17)	no data	0.612±0.057	no data
			--	NS	--
LARIDAE					
Larus argentatus smithsonianus (3,6,4,2), Herring Gull[6]					
Great Lakes	pre-'47	456(369)	6.07±0.06	0.375±0.002	1.73±0.01
Great Lakes	1947-48	14(14)	5.93±0.25	0.375±0.012	1.66±0.05
			NS	NS	--
Great Lakes	1951-58	28(22)	5.78±0.13	0.349±0.007	1.59±0.04

TABLE 7 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			-5%	-7%	-8%
Great Lakes	1960-69	190(151)	5.56±0.10	0.338±0.004	1.55±0.02
			-8%	-10%	-10%
Atlantic Coast	pre-'47	598(513)	6.29±0.05	0.372±0.002	1.77±0.01
Atlantic Coast	1963-69	41(41)	5.98±0.21	0.369±0.008	1.68±0.04
			-5%	-1%	-5%
Arctic No. Amer.	pre-'47	103(94)	6.52±0.11	0.384±0.004	1.80±0.02
Arctic No. Amer.	1954-62	12(3)	6.12±0.26	0.397±0.014	1.69±0.06
			-6%	+3%	-6%
STRIGIDAE					
Bubo virginianus (5,7), Great Horned Owl					
B. v. pallescens					
So. California	pre-'47	280(44)	4.49±0.05	0.360±0.006	1.90±0.02

TABLE 7 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
So. California	1947-59	31(0)	4.68±0.14	no data	1.91±0.05
			NS	--	NS
Texas, Mexico	pre-'47	192(67)	4.97±0.07	0.369±0.005	1.97±0.03
Texas	1950-52	16(0)	4.84±0.20	no data	1.90±0.08
			NS	--	NS
B. v. pallescens - occidentalis					
Western Desert - Great Basin	pre-'47	93(40)	4.73±0.10	0.368±0.005	1.94±0.03
New Mexico, Utah	1947-66	46(0)	4.85±0.12	no data	1.93±0.05
			NS	--	NS
B. v. occidentalis - virginianus					
Interior - Midwest N. Amer.	pre-'47	195(134)	5.21±0.10	0.379±0.008	2.01±0.03
Montana, Utah, Alta.	1954-67	17(11)	4.99±0.32	0.365±0.018	1.94±0.12
			NS	NS	NS

TABLE 7 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
Ontario	1954-68	17(7)	5.20±0.27	0.366±0.015	1.87±0.09
			NS	NS	--
B. v. virginianus					
Florida	pre-'47	67(20)	5.05±0.10	0.354±0.009	1.89±0.03
Florida	1949-52	27(0)	4.50±0.16	no data	1.66±0.04
			-11%	--	-12%
Florida	1957-68	8(0)	4.11±0.21	no data	1.56±0.06
			-19%	--	-17%
CORVIDAE					
Corvus brachyrhynchos (3), Common Crow					
C. b. hesperis - brachyrhynchos					
No. Prairie, Aspen Parkland	pre-'47	132(71)	1.17±0.02	0.202±0.004	0.97±0.01
Alberta	1947	5(3)	1.33±0.10[7]	0.217±0.029	1.09±0.04[7]

TABLE 7 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			+13%	+7%	+11%
Alberta	1960-62	67(0)	1.14±0.03	no data	0.92±0.03
			-2%	--	-5%
C. b. hesperis					
Pacific Northwest	pre-'47	75(7)	1.16±0.03	0.217±0.009	0.94±0.01
Oregon	1950	5(0)	1.13±0.08	no data	0.91±0.02
			NS	--	NS
California	pre-'47	234(44)	1.08±0.09	0.200±0.005	0.95±0.07
California	1948-49	19(0)	0.99±0.05	no data	0.88±0.03
			NS	--	NS
California	1953-56	8(0)	1.08±0.06	no data	0.91±0.05
			NS	--	NS
Am. Southwest	pre-'47	85(49)	1.14±0.03	0.206±0.006	0.93±0.02

TABLE 7 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
New Mex., Wyoming	1956	9(0)	1.26±0.09[7]	no data	1.02±0.04
			+10%	--	+10%
C. b. brachyrhynchos					
Great Lakes, Midwest	pre-'47	236(105)	1.23±0.02	0.214±0.003	1.00±0.01
Ontario	1947-50	30(0)	1.17±0.04	no data	0.98±0.02
			-5%	--	-2%
Ontario	1951-59	40(0)	1.22±0.04	no data	0.98±0.02
			NS	--	NS
Ontario	1960-64	64(0)	1.19±0.04	no data	0.96±0.02
			-4%	--	-4%
C. b. pascuus - paulus					
Florida	pre-'47	149(21)	1.24±0.02	0.200±0.005	0.98±0.01
Florida	1948	9(0)	1.25±0.08	no data	1.00±0.08

TABLE 7 Continued.

Family[2] Species, Subspecies (Foods[3]) Region Involved	Period	Sample Size[4]	Means ± 95% C.L.'s, Changes: Shell Weight (g)	Shell Thickness (mm)	Thickness Index[5]
			NS	--	NS
Florida	1950-53	18(0)	1.33±0.09	no data	0.98±0.04
			NS	--	NS
Florida	1959-61	25(0)	1.22±0.05	no data	0.98±0.02
			NS	--	NS

[1] All footnotes follow those of Table 1, excepting footnotes 6 and 7.

[6] From Anderson and Kreitzer (1970) and Anderson et al (1970b).

[7] Significant differences possibly due to sampling error or inadequate egg-cleaning?

TABLE 8. Interspecific differences in thickness as it relates to egg levels of DDE or DDT-family residues[1] found in field specimens.

Species	Locality	Approx. residue level(A)[2]	Change(B)	A/B ratio	Reference
Aquila chrysaëtos	Montana	7	0%	-	Seidensticker & Reynolds, 1970
Larus argentatus	Atlantic Coast	30	0%	-	Hickey & Anderson, 1968
Pelecanus erythrorhynchos	Interior No. Amer.	34*	-4%	9	Anderson et al., 1969
Buteo jamaicensis	Montana	64	-12%	5	Seidensticker & Reynolds, 1970
Falco mexicanus	Colorado	72*	-14%	5	Enderson & Berger, 1970
Falco mexicanus	Alberta, Sask.	85*[3]	-11%	8	Fyfe et al., 1969
Phalacrocorax auritus	Interior No. Amer.	208*	-8%	26	Anderson et al., 1969
Falco peregrinus	Ungava	253	-21%	12	Berger et al., 1970
Ardea herodias	Alberta	771*	-11%	70	Vermeer & Reynolds, 1970
Larus argentatus	Wisconsin, 1967	972*	-10%	97	Hickey & Anderson, 1968
Pelecanus occidentalis	California	1225	-34%	36	Keith et al., 1970
Pelecanus occidentalis	California	2250*	-53%	43	Risebrough et al., 1970
Larus argentatus	Wisconsin, 1964-5[4]	2525	-19%	133	Keith, 1966; Anderson et al., 1970b

Table 8 continued.

TABLE 8 continued.

1/ DDE was the predominant chlorinated hydrocarbon insecticide, or insecticide-related compound, found. If the residue level is marked with an asterisk, DDE or DDT-family residues were found to be negatively correlated with thickness or its index.

2/ Residues expressed as ppm lipid-basis, most of which were converted by us if data were not available, assuming an approximate lipid level in eggs of 6 to 7 percent.

3/ Included all chlorinated hydrocarbon insecticides of which DDE was predominant.

4/ The residue level was reported for 1964 only. Both values represent those from intact eggs; broken eggshells (3) had thinned 31%.

APPENDIX

GEOGRAPHICAL VARIATION IN THE EGGSHELLS OF COMMON LOONS

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INTRODUCTION

Our major objective here is to report geographical variations in the eggshells of Common Loons (Gavia immer). The data, besides being of interest from an academic viewpoint, have a potential practical application. Numerous authors have recently reported eggshell changes, namely in shell thickness and weight, in certain bird species. These findings dictated, but not necessarily so, that our cutoff date in analysis of "normal" geographic variation be no later than 1946 (see Ratcliffe 1967, and Hickey and Anderson 1968).

INDICES TO GEOGRAPHICAL VARIATION

Rand (1947) has used two criteria to report geographical variation in the Common Loon, bill length and wing length, the latter being more, but not entirely satisfactory. The wing-chord measurements of Rand (1947), although somewhat variable, were adequate to suggest geographic variation in size on an intraspecific basis in North American Common Loons. Despite potential weakness in the use of wing chord as an index to body size (see Welty 1964:457-58 and Scholander 1955), it seems generally satisfactory (Mayr 1956 and Amadon 1943a), especially on an intraspecific basis. Since many readily taken eggshell measurements (such as volume, thickness, and weight) often seem to relate to body

size on an intra- and even sometimes on an interspecific basis (Romanoff and Romanoff 1949:150, Amadon 1943b, Lack 1968:235, Anderson and Hickey 1970), most of our measurements here probably reflect body size. The general relationship between wing chord and body size reported by Rand (1947), then, provided us with a basic hypothesis to test statistically, applying our eggshell data to an already hypothesized trend.

MATERIALS AND METHODS

Eggshells were measured from various museums throughout North America as already described by Anderson and Hickey (1970). The basic variables we examined were as follows: empty-eggshell weight including membranes, egg length (L), egg breadth (B) at its widest portion, L/B ratio, estimated outside volume, and eggshell thickness including membranes and cuticle. Tyler (1969) has described in detail the shell structure of Gaviiformes and it is obvious that our measurements of thickness encompassed many various structures. Amadon (1943b) described various methods used to obtain measurements relating to egg volume. We estimated volume on the basis of the shape categories described by Preston (1953) and Palmer (1962:13) and the constant LB^2 as discussed by Amadon (1943b). Examples (10 to 11 each) of the two shape categories we found in loons, subelliptical and oval, were immersed in water for a volumetric determination of outside volume. Cylinder volumes with equivalent L and B measurements of each egg were calculated and a correction factor (CF) for each shape determined. We originally planned to calculate a CF-regression formula for differing L/B ratios within each shape category, but found them to be remarkably agreeable within the ranges we tested, and therefore combined them. The resultant CF's

were as follows: subelliptical = 0.64, oval = 0.62. We multiplied these by the volume of a cylinder of equal L and B for each egg to obtain our estimate of volume. This procedure is essentially similiar to that described by Stonehouse (1963). The hypothesis which we tested is restated as follows: (1) geographic variation in eggshells occurs in North American Common Loons, and (2) it occurs according to the trends (wing chord as an index to body size) described by Rand (1947). Statistical tests were (1) analysis of variance, and (2) Duncan's new multiple-range test (Steel and Torrie 1960:112-15, 107-09). The hypothesized trends are summarized in Fig. 1 as we vision them from Rand's descriptions.

RESULTS AND DISCUSSION

Eggshell Measurements

All six variables tested showed highly significant differences ($P<0.01$) between our various subjective groupings used to test for clinal variation (Table 1). The F-test generally confirms Rand's (1947) description of variation in Common Loons. The Duncan's-test, although not entirely satisfactory because of its one-dimensional character, yielded additional information regarding a description of the variation (Table 2). Volume comparisons (Table 2), for example, gave 12 significant differences in 21 tests, whereas only 1-2 would be expected at the 95% level due to sampling error. Eggshell weight, volume, and thickness generally followed similiar trends which were much alike and in accordance with previously described trends. Since eggshell weight, volume and thickness are generally interrelated parameters on an intraspecific basis (Asmundson and Baker 1940, and

FIGURE 1. Map showing trends in the wing-chord measurements of Common Loons as described by Rand (1947)--dotted line. The breeding range of Gavia immer is adapted from Palmer (1962:27) and Godfrey (1966:10) with modification from the AOU Check-list (1957) concerning California. Circles indicate, subjectively, relative differences in wing chord, and arrows point to increases in the trend. Solid lines enclosing geographical regions represent subjective groupings as we would see them for statistical testing and as best fitting our sample distributions. Eggshells from area 5 represented inland nests, and Ontario eggs from the Great Lakes were included in area 4. Areas of especially noticeable overlap in measurements, according to Rand (1947), are between 5 and 6 and between 1 and 3.

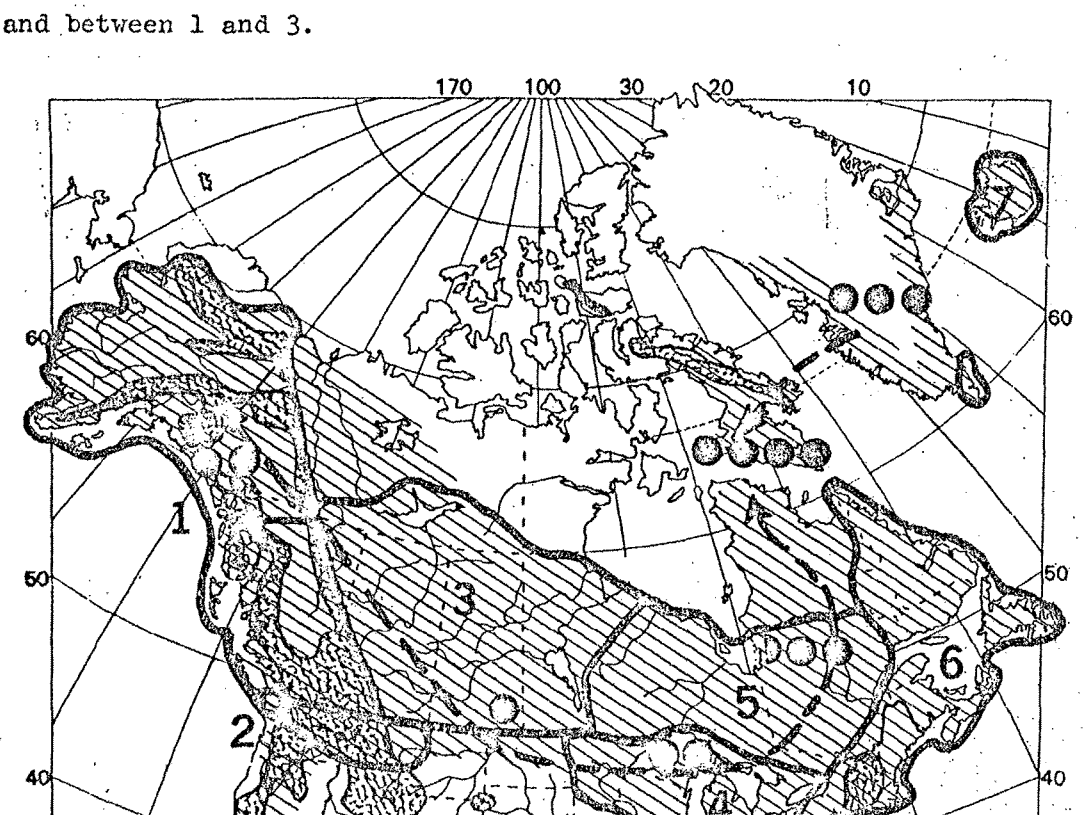

TABLE 1.--Analyses of variance, comparing six eggshell variables in Common Loons over seven geographical areas

Variable Name	Degrees of Freedom: Among	Within	F-value[1]
Eggshell wt. (g)	6	295	20.44
Length (cm)	6	295	7.77
Breadth (cm)	6	295	22.86
Length/Breadth	6	295	5.33
Volume (cm^3)	6	295	23.31
Thickness (mm)	6	239	7.15

[1]F-values at various significance levels are as follows (Steel and Torrie 1960:440): P.05 = 2.10, P.01 = 2.80.

TABLE 2.--Geographic variation in four eggshell variables of Common Loons from seven geographical areas

Geographical Area[1]	Sample Size[2]	Variable Mean ± 95% Confidence Limits and Differences:[3]							
		Weight	Test	L/B	Test	Volume	Test	Thickness	Test
1	32(24)	16.8±0.5	ABC	1.54±0.04	E	143.7±3.5	BC	0.64±0.01	ABC
2	10(9)	15.5±1.4	DEF	1.58±0.04	BCDE	130.9±8.7	F	0.63±0.04	BCDE
3	70(42)	14.3±0.3	F	1.60±0.02	AB	128.0±2.4	F	0.60±0.01	EF
4	49(39)	15.6±0.4	DE	1.58±0.03	BCD	140.5±3.3	CDE	0.61±0.02	EF
5	69(60)	16.1±0.5	BCD	1.62±0.02	A	142.7±3.0	BCDE	0.63±0.01	BCD
6	38(38)	17.1±0.5	AB	1.61±0.03	ABC	146.3±2.9	AB	0.65±0.01	AB
7	34(34)	17.4±0.7	A	1.56±0.02	DE	150.3±4.0	A	0.66±0.02	A

[1]Areas are numbered in accordance with Fig. 1 with sample locations as follows: 1 = Aka., B.C.; 2 = Wash., Ida., Mont.; 3 = Alta., Man.; 4 = Minn., Mich., Wisc., Ont.; 5 = Ont., southern Que.; 6 = Me., N.H., N.Y., N.S., Lab., Nfld.; 7 = Iceland, eastern Greenland (see Palmer 1962:27 for justification in combining these).

[2]No. in parentheses is sample size for thickness only.

[3]Means not significantly different from one another share a common letter in the "test" column.

Asmundson et al. 1943), similiar trends are to be expected. The general uniqueness of middle groups (geographical areas 2, 3, and 4, Fig. 1) with significant differences moving out in both directions from those areas, suggests a linear, but branching variation either converging or diverging from that area, possibly related to latitude and Bergmann's Rule. Even though, in all cases, the values on each end of the spectrum were not significant statistically from one another on a ranked basis, we believe them to be biologically significant due to their geographical separation. Perhaps two statistical tests would have illustrated the data better, using these interior areas as a "starting point" for each. The patterns observed with weight, volume, and thickness seemed nearly opposite to those observed with L/B ratios, but by no means were the differences large or of sufficient magnitude to yield noticeable differences except from the interior areas (5 and 6) out toward each extreme. The large F-value for breadth as compared to length (Table 1) suggests that B is the most variable. Somewhat different L/B ratios, in any case, suggested possible differences in the shape distributions from area to area. We tested this hypothesis with Chi^2 and found that significant differences occurred in a pattern generally similiar to that observed for differences in the L/B ratios. Areas 5 and 6 (Fig. 1) tended to have significantly different distributions of the two shape categories (area 5 was significantly different, $P<0.05$, from areas 2, 3, 4, and 7; area 6 was significantly different from 3). L/B ratios (Table 2) from area 5 were not significant only from adjacent geographical areas, 3 and 6. When areas 5 and 6 were combined and tested against the remainder in a 2 x 2-table, it was found that their tendency toward a larger proportion of subelliptical

eggs was significantly different ($P<0.01$, $Chi^2 = 21.3$). The mean ratio of subelliptical/oval in areas 5 and 6 was 0.56 as compared to 1.74 in the remainder of the areas. Since areas 5 and 6 tended to have the higher L/B (Table 2; admittedly, there is a great deal of overlap, and differences are only slight), our tentative conclusion is that different tendencies in L/B ratios must at least in part be related to different shape tendencies. The loon eggs with the greatest L/B ratios were the eggs which tended more toward subelliptical and those with the smallest L/B ratios tended more toward oval.

Clutch-size

Much discussion has been presented regarding geographical variation in clutch-size (see Lack 1954, 1968; Cody 1966; and others). There seemed to be little difference between the mean clutch-size between most areas, except in our samples from area 5, where differences seemed apparent ($P<0.05$ differences from all but 1 and 2). There appears to be a rough trend for clutch-size to increase out from this area (Table 3). When areas 1 and 2, and 3 and 4 were analyzed singly, no differences or even trends could be found, thus their combinations in Table 3. Unfortunately, we had no data from Greenland, Baffin Island, or Northwest Territories to test for further changes in the trend. Mean egg volume showed no relationship to clutch-size due to the variability in clutch-size. We do not know, however, if the clutch-size data were biased by failure to collect one-egg clutches in some areas. Such clutches are reportedly fairly common for G. immer (see Olson and Marshall 1952, and Palmer 1962:31). We doubt that our Iceland sample, for example, truly represented the tendency for a lack of one-egg

TABLE 3.--Clutch-sizes of Common Loons from various geographical areas

Geographical Area[1]	Sample Size	Mean Clutch-size	95% Confidence Limits
1 + 2	23	1.87	0.15
3 + 4	65	1.92	0.07
5	58	1.64	0.14
6	20	1.95	0.10
7	17	2.00[2]	0.00
all	183	1.84	0.06

[1]See Table 2, footnote 1.

[2]All clutches we found in museums were composed of two eggs, therefore the zero values for 95% Confidence Limits. Most of these eggs were collected by one collector, and might be biased away from single eggs.

clutch from Iceland. We believe that additional data to increase sample-sizes are necessary before conclusions can be made relating clutch-size to some geographical gradient or to egg volume in loons. There is good reason to believe that these relationships exist (see Lack 1968:233-34 and Mayr 1965:325).

GENERAL DISCUSSION

The data presented in this paper confirm geographic variation in various eggshell measurements of the Common Loon. The eggshell measurements which most likely relate to body size showed the same trends as described by Rand (1947) for other measurements relating to body size. Snyder (1957:26) recognizes a "limited" correlation between size and latitude in Common Loons, but stresses that considerable overlap occurs in intermediate areas. Todd (1963:75) discounted any evidence of a cline in this species on the basis of bill and wing measurements, but suggested trends, nonetheless. He did not believe that smaller forms to the south should be recognized taxonomically due to a considerable overlap in measurements. This was in agreement with Rand (1947). We do not believe that the regions we tested here on a statistical basis are biologically discreet, due to the overlaps in significance between neighboring regions. Two or more general latitudinal continuums probably best describe our data on a purely subjective basis, possibly one each on each side of Hudson Bay. The clines do not seem related to latitude on a strictly quantitative basis, however. The western regions seem to show less variation with the same amount of latitude that shows greater variation in the east, especially when Baffin Island birds are theoretically considered (we did not have

eggshells from this area). The isophenes (see Mayr 1965:362) of, say, egg volume might be visioned as shown in Fig. 2. We regard the clinal variation described here for the Common Loon to be "ecotypic" as described by Mayr (1956, 1965:415) and therefore probably of little taxonomic relevence (Mayr 1965:363). It is interesting that in the area of proposed isolines outside the breeding range of Common Loons (dotted lines in northwestern and north-central North America, Fig. 2), another species, G. adamsii, breeds (Rand 1948). Palmer (1962:35) reports that G. adamsii is the largest of our loons, but eggshell measurements are nearly identical, comparing the two species (Palmer 1962:31, 40). Godfrey (1966:11) does not believe there is sufficient justification to consider these two allopatric species as "mere races of the same species", as proposed by some authors, and it appears that eggshell measurements might help justify this conclusion in demonstrating different body-size/egg-size ratios. Studies concerning the eggshells of G. adamsii are needed.

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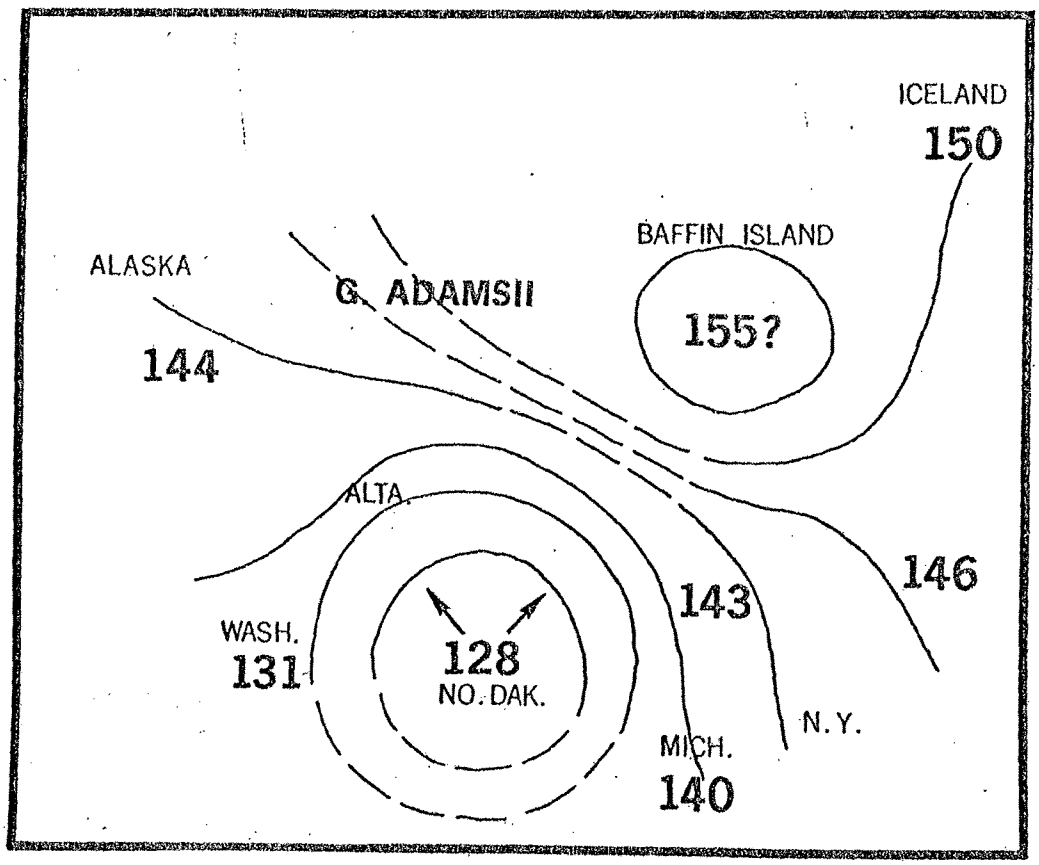
FIGURE 2. Hypothesized isophenes for eggshell volume in Common Loons, assuming that the clines as we interpret them generally cross the isophenes at right angles (Mayr 1965:362). This figure is only roughly sketched and on the same scale as Fig. 1. The values given are mean volumes from each area. The value for Baffin Island is strictly hypothetical but assumes that this deme, having the largest individuals (Rand 1947), will have the largest eggs.



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OOLOGICAL DATA ON EGG AND BREEDING CHARACTERISTICS OF BROWN PELICANS

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OOLOGICAL DATA ON EGG AND BREEDING CHARACTERISTICS OF BROWN PELICANS

DANIEL W. ANDERSON AND JOSEPH J. HICKEY

THE Gulf Coast population of the Brown Pelican (*Pelecanus occidentalis*) is now considered to be endangered by the AOU Committee on Conservation (1968). The circumstances surrounding its decline are not clear. Murphy (1936:102, 808–822) suggested that some breeding populations of Brown Pelicans "normally" fluctuate in response to fluctuating food supplies in relation to such factors as Humboldt Current changes, as well as other factors. Conney (1967), Kupfer (1967), Peakall (1967), Risebrough et al. (1968), and Wurster (1969) have explained some potential physiological effects of chlorinated-hydrocarbon and related environmental pollutants on mammalian and avian reproduction, which might apply, as well.

This paper presents information, obtained from major oological collections in North America, regarding some egg and reproductive parameters of the Brown Pelican. Ratcliffe (1967) and Hickey and Anderson (1968) have utilized oological sources to document changes in shell thickness and shell weight among seven species of birds. These changes were related to (1) the widespread introduction of persisting chlorinated hydrocarbons into the environment and (2) reproductive failures associated with shell-breakage and loss.

The lack of field data regarding certain breeding and egg characteristics from prior to and possibly during the decline of the Brown Pelican necessitated our attempt to glean whatever information possible from museum and private-egg collections. An understanding of the present situation, in addition, requires an evaluation of the geographical and temporal variations in the characters of interest.

METHODS

Measurements.—Eggs were weighed to the nearest 0.01 gram (g) on a torsion balance. Improper cleaning undoubtedly influences shell-weight and possibly also shell-thickness measurements. We used four criteria to determine if eggs had been properly blown: (1) a tendency to settle to one side when rolled on a smooth surface, (2) loose contents, (3) roughness on the interior of the shell, and (4) visual examination. In the course of measuring over 34,000 eggs of 25 species, we found about 200–300 broken or cracked eggs and a larger number with large holes. These lent themselves to close examination, and all proved to be satisfactorily cleaned. Eggs with holes larger than 7 mm were either not measured, or their weights were corrected to those with a 3-mm hole. This was accomplished by taking a small piece of shell, weighing it, and visually "filling" the hole. Egg lengths and breadths were measured to the nearest 0.01 centimeter with a standard, precision vernier caliper. Egg shapes were determined by comparison with the shapes

TABLE 1

CLUTCH SIZES AND INCUBATION STAGES OF EGGS TAKEN BY OOLOGISTS PRIOR TO 1943

Est. Stage of Incubation	Incubation Rating	Sample Size	Mean Clutch Size	95% C. L.
First egg–3 days[1]	1	72	2.94	0.32
4–12 days	2	137	2.93	0.31
13–21 days	3	27	3.07	0.50
22–30 days	4	0	—	—
All combined	—	236	2.95	0.27

[1] This stage represents a period of approximately 9 days.

described by Palmer (1962:13) and Preston (1968). Shell thickness was measured to the nearest 0.01 mm with a specially adapted micrometer, the procedure being described by Hickey and Anderson (1968). Thickness included shell and associated membranes at the girth of each egg.

Information from Data Slips.—Data slips, giving species, date of collection, stage of incubation, location, collector, and other pertinent information accompanied each set of eggs we measured. Due to the inadequacy of incubation terminology and the inability to identify incubation stage accurately (Storer, 1930), mean dates of set-collection (corrected on the basis of reported incubation to give date of clutch completion) can only provide an estimate of breeding phenology. The dates together for an area really only represent a mean over the years, but do suggest general trends and provide an index to length and variability of breeding season from region to region. We felt that oologists' estimates of incubation could, at best, only be categorized to the nearest one-fourth of the period from first egg to the end of incubation. The incubation period of the Brown Pelican is not precisely known (Palmer, 1962:277). We have used Mason's (1945) estimate of about 30 days for our calculations here and have estimated the mean number of days that our samples were incubated on the basis of our four incubation categories (Table 1, col. 1). In our series of samples, mean stage of incubation in days subtracted from mean date of set-collection provided an estimate of date of clutch completion. Unincubated ("fresh") eggs were included in the analysis of clutch size, after testing to determine if fresh sets might be biased by the collection of incomplete clutches. When sets of fresh eggs were separately compared with those of later incubation (t-test), no significant differences in clutch size were found ($P > 0.05$, Table 1). There remains the possibility that some egg collectors sought larger clutches.

Calculations and Indices.—All data were analyzed with an IBM 1620 computer. Statistical analyses followed Steel and Torrie (1960). A size index for eggs was calculated by multiplying length by breadth and was used as a crude index to volume. In a study of White Pelicans (*P. erythrorhynchos*) (D. W. Anderson and J. J. Hickey, unpublished), we have found displaced volume to be correlated with this size index ($P < 0.001$).

Geographical variations in egg size, shell thickness, shell weight, clutch size, and egg dates were determined in a stepwise manner as follows: (1) current subspecific range boundaries were determined from the AOU Check-list (1957) and Palmer (1962:275), and the range was then subdivided into small geographic units such as a single state; (2) the eggshell data for these were then tested for significant differences and regrouped until a region was obtained containing a maximum number of subunits that were not significantly different from each other; (3) groupings never included more than one

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TABLE 2

GEOGRAPHICAL VARIATION IN EGGSHELLS OF NORTH AMERICAN BROWN PELICANS, 1879 TO 1943[1]

Subspecies / Area	occ West Indies	car S.C.	car Fla., Ga.	car La.	car Panama	car Texas	cal Baja Calif.	cal So. Calif.
Number	6	43	208	42	7	115	174	85
Wt. (g)	8.05	9.46	9.78	9.87	9.94	10.00	10.99	10.59
±95% C.L.	±0.90	±0.35	±0.12	±0.32	±0.49	±0.26	±0.18	±0.24
Size Index (cm^2)	33.2	37.6	37.6	38.2	37.4	38.5	40.0	39.0
±95% C.L.	±0.6	±0.9	±0.3	±0.7	±1.0	±0.6	±0.4	±0.7
No. Subelliptical	3	21	109	20	2	52	94	44
No. Oval	3	22	99	22	5	63	80	41
Thickness Index[2]	2.42	2.52	2.60	2.58	2.66	2.59	2.74	2.71
±95% C.L.	±0.24	±0.06	±0.02	±0.06	±0.10	±0.04	±0.02	±0.04
Number	6	23	172	24	—	43	83	28
Thickness (mm)	0.510	0.557	0.557	0.554	—	0.557	0.569	0.579
±95% C.L.	±0.031	±0.021	±0.004	±0.014	—	±0.012	±0.008	±0.014

[1] The pre-1943 means that were not significantly different at the 95% level in Duncan's New Multiple Range Test (Steel and Torrie, 1960:107–109, 114) are underscored.
[2] From Ratcliffe (1967): Thickness index = 10 × wt. in g/(length × breadth in cm).

described subspecies; and (4) phenological subdivisions were kept at the smaller units without regrouping.

RESULTS AND DISCUSSION

Geographical Variation in Egg Parameters.—Egg-size index, shell weight, and shell thickness (Table 2) tended to vary with the size of the bird as discussed by Romanoff and Romanoff (1949:150). Our index to body size was obtained by using two common standard measurements that tend to measure skeletal size (tarsus and culmen) (Fig. 1). These skeletal measurements were taken from Wetmore (1945) and represent those of female birds. Wetmore (1945) ranked the size of the three North American subspecies, from largest to smallest as follows: *P. o. californicus*, *P. o. carolinensis*, and *P. o. occidentalis*.

The general shape categories (Table 2) were, nonetheless, not significantly different ($P > 0.05$, Chi-square test) from area to area or between subspecies. Ordinary shape changes in the eggs of domestic poultry have already been shown to have little effect on the shell present as a percentage of total egg weight (Asmundson and Baker, 1940).

Of the subspecies *carolinensis*, birds from Texas tended to have the largest

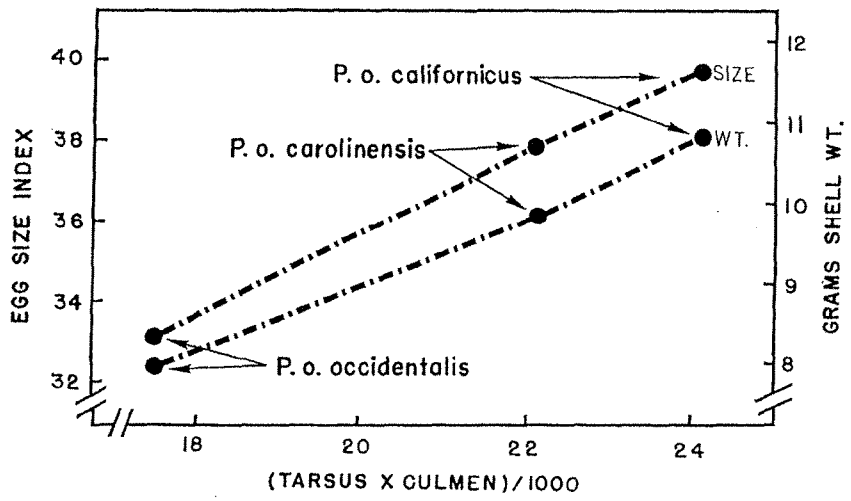

FIG. 1. Relationship between two egg measurements and index to body size in three subspecies of Brown Pelicans. The index to body size was calculated in mm^2 units and is shown on the abscissa. Eggshell size was taken as the product of length and breadth in cm^2.

eggs. Louisiana eggs tended to be intermediate between those from Texas and those from areas to the east (Table 2). South Carolina birds tended to have smaller and lighter-shelled eggs than birds from farther south in Florida and Georgia, although not significantly so (Table 2). The Baja California eggs (*P. o. californicus*) were represented mostly by specimens from Los Coronados Island but suggested a similar gradient, with egg size decreasing from southern to northern colonies. Lack (1968:279) mentioned this trend among certain congenerics in certain tropical Procellariiformes. A continuum in egg size and shell weight between different populations from different areas was suggested in our specimens, especially in *carolinensis*, although shell thickness in the various subspecies seemed relatively stable. Whether or not the intrasubspecific tendencies are genetic is unknown. They are likely genetic, but standard measurements from museum skins are needed for further comparisons. The intersubspecific variations in egg size are most likely representative of body size (Fig. 1).

If one assumes that egg size provides an index to body size, the large Texas birds may represent an intermediate between *californicus* and *carolinensis*. Brown Pelicans along the Pacific Coast (*californicus*) have the larger and thicker-shelled eggs (Table 2). Asmundson et al. (1943) showed that larger eggs in several species tended to have the thicker shells, but the essentially

equal thicknesses from all our Gulf and Atlantic Coast eggs suggested that this relationship was not present on an intrasubspecific basis. The small sample of eggs from Panama suggested that these eggs were most similar to the subspecies *carolinensis*, as Wetmore (1945) has shown with museum skins. Unfortunately, we were unable to obtain egg measurements from Ecuadorian or Peruvian Brown Pelicans. Murphy (1936:820) reported that the Peruvian pelicans are very large and we suspect that their eggs would also be larger and thicker-shelled.

The ecological significance of egg-size difference within a species is largely a matter of speculation. Lack (1966:7) suggests that egg-size differences between different species (and larger groups) are mainly a matter of heredity. The differences we observed on an intersubspecific basis in Brown Pelicans at least implied that these eggs are represented by relatively distinct gene-pools. Perhaps such gene-pools are even distinct on an intrasubspecific basis. Mason (1945) showed that Florida Brown Pelican movements, at least, are somewhat restricted under normal circumstances, suggesting potential isolation between breeding groups. Welty (1962:408 quoting Murphy, 1936) also suggests that this species is potentially sensitive to isolating barriers.

Possible Factors for Bias.—It is not our primary objective here to speculate on taxonomic relationships on the basis of eggs; nonetheless, the variations in eggs are expected to relate in some ways to taxonomic characters (Tyler, 1964, 1965). Our interest is mainly to examine natural variation in order to better understand if unnatural change has occurred.

Egg size and shell thickness and composition are known to vary with heredity, age, adult physiological condition, diet, and chemical influence (Romanoff and Romanoff, 1949:152–157, 359; Preston, 1958; Sturkie, 1965: 464, 487–488; Simkiss, 1967:157–197). Shell thickness also varies in different areas of the egg of a given species, the most notable examples probably being the rock-nesting murres (*Uria* sp.) and other seabirds, where thickness tends to increase at the most vulnerable parts (Tuck, 1960:25). Some interspecific differences in thickness have been shown to be related to the hazards associated with placement on different nesting substrates (Belopol'skii, 1957: 133–134). Fortunately, egg collectors drilled their specimens at the girths, the most uniform area for most species (Romanoff and Romanoff, 1949: 157–158).

Shell calcium (about 5 per cent) is utilized, as well, by developing embryos (Simkiss, 1967:198–213); hence, shell weight and also possibly thickness may be biased low if eggs of late-stage incubation are used in the shell-thickness or weight comparisons. Data combined into *carolinensis* and *californicus* categories indicated this trend (Table 3), although not significant statistically (t-test, $P > 0.05$) and only amounting to a small percentage

TABLE 3

SHELL WEIGHTS OF PRE-1943 EGGS OF TWO SUBSPECIES OF BROWN PELICAN AT DIFFERENT INCUBATION STAGES

Subspecies Incubation Stage	No.	Mean Wt. (g)	95% C.L.
carolinensis			
First egg–3 days	98	9.75	0.21
4–12 days	230	9.88	0.14
13–21 days	53	9.76	0.28
californicus			
First egg–3 days	92	10.75	0.20
4–12 days	121	10.97	0.25
13–21 days	30	10.59	0.40
Both			
First egg–3 days	190	10.23	0.16
4–12 days	351	10.26	0.14
13–21 days	83	10.06	0.24

in our sample (1–3 per cent). Therefore, we do not believe this bias to be important in the oological data examined here. Furthermore, the data suggested that most egg collectors tended to collect eggs that were about one-third or less incubated (Table 1), thus eggs in late-stage incubation represented a small percentage of our sample. Although effects on the egg stemming from the age and physiology of the laying female would remain undetectable in oological samples, they would not be expected to affect an overall random, or essentially random, sample (see Asmundson et al., 1943).

Eggshell Changes and Pesticide Residues.—The small samples of post-1949 specimens suggested thinning in all eggshells measured (Table 4). Florida specimens showed a –17 per cent change in shell weight, Texas specimens a –20 per cent change, California specimens (Anacapa Is.) a –26 per cent change, and one set of eggs from Panama a –15 per cent change. All were significant ($P < 0.05$) changes. We could detect no change in shape in these post-1949 eggs ($P > 0.05$, Chi-square test). The incubation stages were essentially the same for both pre-1943 and post-1949 eggs (6 ± 2 days *vs.* 9 ± 5 days, 95 per cent C.L.). Size indices were not significantly different ($P > 0.05$), although the post-1949 eggs from Texas and Florida were slightly smaller in mean than those of pre-1943. Whether or not these changes in weight and thickness were associated with either recent declines of the Brown Pelican or environmental pollution, or both, remains to be determined.

Stickel (1968) has stated that in Gulf Coast Brown Pelicans, pesticide residues were of approximately the same general magnitude as those of herons

TABLE 4
POST-1949 EGGSHELL MEASUREMENTS OF BROWN PELICANS[1]

Subspecies Area	*carolinensis* Florida	*carolinensis* Texas	*carolinensis* Panama	*californicus* California
Number	9	6	3	9
Wt. (g)	8.10	7.96	8.45	7.89
±95% C.L.	±0.14	±0.60	±0.99	±0.66
Size Index (cm^2)	36.5	37.6	37.6	39.0
±95% C.L.	±0.9	±2.4	±2.0	±1.4
No. Subelliptical	1	2	2	7
No. Oval	8	4	1	2
Thickness Index[2]	2.22	2.12	2.25	2.02
±95% C.L.	±0.09	±0.10	±0.22	±0.12
Number	—	—	3	9
Thickness (mm)	—	—	0.457	0.424
±95% C.L.	—	—	±0.012	±0.018

[1] Post-'49 eggs were collected as follows: Florida—1950, 1953; Texas—1951; Panama—1952; California—1962.
[2] From Ratcliffe (1967): Thickness index = 10 × wt. in g/(length × breadth in cm).

(*Ardea cinerea*) from Great Britain and Bald Eagles (*Haliaeetus leucocephalus*) in the United States (see Stickel et al., 1966; and Moore and Walker, 1964). Risebrough et al. (1967) analyzing two Brown Pelican eggs from the Gulf of California found them to be generally "low" in pesticide content (0.7 ppm [wet-weight basis] DDT and metabolites and about one-fifth as much polychlorinated biphenyls [PCB's], an industrial pollutant; endrin and dieldrin were also identified). They found an average of 0.8 ppm DDT-family residues (61 per cent DDE) and about two-thirds as much PCB in six Brown Pelican eggs taken in Panama. We converted the above residues to a ppm wet-weight basis by assuming 7 per cent fat in the eggs. We measured two of the eggshells from Risebrough's study (Baja California specimens) and found one suggestive of a "normal" egg (11.7 g, 0.59 mm in thickness) and the other suggestive of thinning (9.3 g, 0.50 mm). Another study (Anderson et al., 1969) showed that egg residues as low as 1 ppm of DDE, and possibly less, could be associated ($P < 0.05$) with detectable shell changes in White Pelicans, although egg residues may not always necessarily reflect residues in adults that could influence egg-shell deposition. Risebrough et al. (1967) reported 84.4 ppm of DDT-type residues, 91 per cent of which was *p,p'*-DDE (77 ppm) in the breast muscle of a Brown Pelican collected in California. These levels are only slightly lower than those reported from Lake Michigan Herring Gulls (*Larus argentatus*), which averaged 80 ppm DDE in the breast of adult birds (Hickey et al., 1966). Reproduction in the

TABLE 5
MEAN DATES OF CLUTCH COMPLETION IN BROWN PELICANS FROM VARIOUS GEOGRAPHICAL AREAS

Area	No. Clutches	Mean Date ± S.D.	Mean Stage Incubation[1]
So. California	29	8 April ± 16 days	1.4
No. Baja California	61	10 April ± 54 days	1.8
Texas	36	9 May ± 18 days	1.5
Louisiana	14	27 April ± 31 days	1.6
Florida	75	29 May ± 125 days	1.9
South Carolina	14	5 June ± 17 days	1.7

[1] Numerically coded with Table 1, cols. 1–2.

Wisconsin Herring Gull population in Green Bay (characterized by egg-breakage) is known to be severely affected by DDE and other residues (Keith, 1966; and Hickey and Anderson, 1968). Egg residues from the same population averaged 183 ppm DDE in 1963 and 1964 (Keith, 1966).

Breeding Characteristics.—Pacific Coast data suggested that between northern Baja California and California, the breeding dates were somewhat closely related (Table 5). Gulf and Atlantic Coast birds, on the other hand, showed much variation, especially in Florida (Appendix 1) as discussed by Bent (1922:295) and Palmer (1962:277). Palmer's (1962:275) distribution map suggests that on the Pacific Coast, the major breeding populations of *californicus* are concentrated into a smaller area than those from Gulf and Atlantic Coast sites (*carolinensis*). Bent (1922:296), Howell (1932:85–87), and Lowery (1960:113–114) noted that Brown Pelicans of the subspecies *carolinensis* tended to utilize trees as well as coastal beaches and islands as nesting substrates. Murphy (1936:810–814) mentioned diverse breeding sites for South American pelicans as well. The Brown Pelicans of northern Baja California and California seem more generally restricted to ground-nesting on islands (Bent 1922:301; Williams, 1927). Bond (1942) reported tree-nesting for the California Brown Pelican as very unusual.

In Florida, where the Brown Pelican still persists (Williams and Martin, 1969), a long breeding season and diversity of nesting substrate seem to characterize breeding. They nest year-round in Peru, although considerable shifting of sites occurs (Murphy, 1936:821–822). The Gulf of California Brown Pelicans still persist as breeders, although there is no evidence of a longer breeding season than in colonies farther north (R. W. Risebrough, pers. comm.).

Clutch sizes showed no significant variation ($P > 0.05$) between any of the geographical areas listed in Table 2. The means, and our best estimates for clutch-size in the Brown Pelican, are given in Table 1. Bent (1922:297)

and Palmer (1962:277) stated that three eggs, and less often two, is the normal clutch size; nests with four and five eggs have been found.

Breeding Records.—The population estimates by egg collectors cited in Appendix 1 must be viewed cautiously. These estimates were subject to observer error; however, they can provide an approximation of changes that might have occurred. Data-slip information, although most likely sketchy, can also provide documentation of past breeding locations. The records we found in egg collections did not provide a complete picture of breeding localities but suggested possible fluctuations in numbers over the years (Appendix 1). On the other hand, none of the major colonies seem to have been completely without birds since at least the late 1800's. Numbers probably increased on Anacapa Island, California, during the late 1920's. Williams (1927) reported a colony as far north as Point Lobos, California, during this time. The late 1920's may represent a period of population increase. Bond (1942) reported the estimated numbers on Anacapa Island from 1898 to 1941 to be highly fluctuating (estimates ran from about 200 to at least 2000 pairs). Banks (1966) reported eggs and young on Anacapa and essentially "normal" numbers of breeding birds, at least in 1963 and 1964, two years after the thin-shelled eggs reported here. The Los Coronados birds seem historically more stable (Appendix 1). It is certain that both Anacapa and Los Coronados breeders were historically present in large numbers (Banks, 1966). Risebrough (1968) and Schreiber and DeLong (1969) suggested that the Brown Pelican has decreased considerably in recent years off California, including no known breeders on Los Coronados in 1968. Perhaps the −20 to −26 per cent figure in shell change represents or approaches the lower limit to which eggs may survive to be collected by egg-collectors. Certainly, some production occurred in the California colony with these shell-changes, although present numbers suggest a declining population. Lowery (1960:113–114) mentions large colonies in Louisiana; yet Winckler (1968), in a popular article, summarized their nearly virtual disappearance from the Gulf Coast by 1968. In the light of the better-known demise of Gulf Coast Brown Pelicans, we believe the status of California Brown Pelicans and populations farther to the south needs immediate study.

SUMMARY

Mean clutch size in 236 sets of North American Brown Pelican eggs was 2.95 and did not vary geographically between North American populations. Shell weight varied from 8.05 g to 10.99 g along a geographic continuum. Shell thickness averaged 0.510 mm for *Pelecanus occidentalis occidentalis*, 0.554–0.557 mm for *P. o. carolinensis*, and 0.569–0.579 mm for *P. o. californicus*. The ranges of breeding dates for the more southern populations were wider than those of northern ones.

Small numbers of eggs taken in Texas and Florida after 1949 were 20 per cent below normal weight; 1962 eggs from California were 26 per cent below normal; and three

taken in Panama, 15 per cent below normal. Shell thickness had likewise decreased 15–27 per cent.

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APPENDIX 1

BROWN PELICAN BREEDING RECORDS TAKEN FROM NORTH AMERICAN OOLOGICAL RECORDS AND COLLECTIONS.

Date	Location	Estimated Numbers; Remarks	Observer	Museum* of record
Southern California				
27 May 1893	Anacapa Is.	—	A. H. Miller	2
5 June 1910	Anacapa Is.	500+ pairs	G. Willett	3,5
7 Mar. 1916	Anacapa Is.	—	M. C. Badger	2
2 Mar. 1917	Anacapa Is.	—	M. C. Badger	3
15 May 1919	Anacapa Is.	—	—	1
7 Mar. 1920	Anacapa Is.	5,000+ pairs	S. B. Peyton	30
8 Mar. 1922	Anacapa Is.	—	S. B. Peyton	5
28 Mar. 1927	Anacapa Is.	—	—	3
24 Feb. 1929	Anacapa Is.	—	C. W. Ashworth	2
1 Mar. 1936	Anacapa Is.	—	E. Harrison	3
1 Mar. 1936	Anacapa Is.	2,000+ pairs	L. T. Stevens	14
12 Mar. 1939	Anacapa Is.	"large colony"	L. T. Stevens	4,7
19 May 1919	San Miguel Is.	—	—	1
25 May 1927	Point Lobos	8–10 nests	L. Williams (1927)	2
Baja California, Mexico				
18 Apr. 1894	Los Coronados	—	E. Parker	27
19 Apr. 1894	Los Coronados	—	—	1
4 Apr. 1895	Los Coronados	—	A. Hewitt	2,22
19 Apr. 1898	Los Coronados	—	A. J. Kellog	24
27 Apr. 1898	Los Coronados	—	—	3
6 May 1904	Los Coronados	—	O. C. Polling	2
6 Apr. 1908	Los Coronados	500 nests	P. I. Osborne	1,4

(APPENDIX 1 CONTINUED)

Date	Location	Estimated Numbers; Remarks	Observer	Museum* of record
6 Apr. 1908	Los Coronados	—	A. Van Rossem	25
1 July 1908	Los Coronados	—	P. I. Osborne	9
4 Apr. 1910	Los Coronados	—	P. I. Osborne	29
2 Apr. 1912	Los Coronados	—	C. S. Thompson	23
1 Apr. 1913	Los Coronados	500 nests	L. M. Huey	3
29 Mar. 1914	Los Coronados	—	W. C. Bradbury	2,9
31 May 1915	Los Coronados	—	I. D. Nokes	5
26 Mar. 1917	Los Coronados	500 pairs	N. K. Carpenter	6
4 May 1917	Los Coronados	—	D. S. DeGroot	2
11 Apr. 1919	Los Coronados	—	N. K. Carpenter	23
12 May 1921	Los Coronados	—	W. C. Hanna	4
30 Mar. 1922	Los Coronados	—	—	1
15 Apr. 1881	Mexican coast	—	—	1
26 Mar. 1917	So. Coronados, SE slope	—	—	1
6 Apr. 1920	Todos Santos Is.	—	G. Bancroft	4
6 Apr. 1920	Todos Santos Is.	—	J. Burnham	26
17 Apr. 1921	San Pedro Nolasco Is.	—	—	1
2 May 1921	Granite Is.	—	—	1
7 Apr. 1932	San Benito Is.	—	E. Harrison	3
10 Apr. 1932	San Martín Is.	—	E. Harrison	3
2 June 1932	Asunción Is.	—	E. Harrison	3
Panama				
15 Feb. 1942	Chama Is., Panama Bay, Panama	—	A. Wetmore	13
15 Mar. 1952	Taboga Is., Panama	—	A. Wetmore	13
Texas				
10 May 1886	Near Corpus Christi	—	F. B. Armstrong	12
20 May 1888	Neuces Co.	—	T. S. Gillin	4
10 Apr. 1889	So. Bird Is., Laguna Madre	—	J. A. Singley	2
16 Apr. 1889	So. Bird Is., Laguna Madre	—	J. A. Singley	4,25
14 June 1894	25 mi. from Corpus Christi	—	F. B. Armstrong	1
14 May 1896	So. Bird Is., Laguna Madre	—	D. B. Burrows	2
28 May 1910	Near Corpus Christi	—	C. E. Farley	30
30 May 1910	Near Corpus Christi	—	J. M. Carroll	4
3 May 1912	Laguna Madre	—	J. M. Priour	4
18 May 1913	Neuces Co.	—	F. B. Armstrong	9
27 May 1915	Padre Is.	—	F. B. Armstrong	2
19 May 1917	Big Bird Is., Laguna Madre	—	R. W. Quillan	19

(APPENDIX 1 CONTINUED)

Date	Location	Estimated Numbers; Remarks	Observer	Museum* of record
May 1919	Is. off so. coast	—	—	3
15 May 1919	Laguna Madre	—	H. Brandt	10
5 May 1922	Neuces Co.	—	G. Stewart	11
24 May 1925	Pelican Is., Aransas Bay	—	R. D. Camp	31
1951	Refugio Co.	—	T. C. Meitzen	18
Louisiana				
29 Mar. 1893	Lost Is.	—	F. A. McIlhenny	2
28 Mar. 1894	Marsh Is.	—	F. A. McIlhenny	2
29 Mar. 1894	Shell Keys	—	F. A. McIlhenny	2,23
3 June 1919	Pass à l'Outre	—	E. R. Kalmbach	13
5 June 1919	Errol Is.	—	J. D. Figgins	9
26 May 1938	North Is.	—	F. Tobin	10
13 Apr. 1940	La Fourche Par., Timbalier	—	G. H. Lowery (1960)	17
Florida				
15 Mar. 1879	Near Marco	—	—	1
1 Apr. 1880	Indian R.	—	C. L. Cass	26
15 Apr. 1880	Indian R.	—	—	1
29 Apr. 1880	Old Tampa Bay	—	—	1
12 Apr. 1890	Lee Co.	—	H. R. Jamison	4
12 Apr. 1890	Charlotte Harbor	—	S. Reiff	21
3 May 1890	W. of Pine Is., Lee Co	225 nests	N. K. Jamison	4
26 Apr. 1891	Pelican Is.	—	M. Gibbs (1894)	9
12 Apr. 1892	Tampa Bay	—	D. P. Ingraham	27
10 May 1893	Pelican Is.	—	J. M. Southwick	4
5 June 1893	Mullett Key	—	B. T. Smith	26
30 June 1894	Tampa Bay	—	—	1
21 Jan. 1896	Pelican Is.	500 pairs	B. W. Evermann	23
3 Apr. 1896	Pelican Is.	—	H. E. Pendry	3
30 Apr. 1896	Seminole Is.	—	H. E. Pendry	5
18 May 1896	Rookery Is., off Diston City	—	W. Meyor	8
15 May 1899	Brevard Co.	—	F. S. Webster	10
19 Apr. 1908	Boca Grande, Charlotte Keys	200 birds	P. B. Phillipp	12
20 Apr. 1908	Charlotte Harbor, Devilfish Key	—	P. B. Phillipp	12
3 May 1911	Pelican Is.	—	P. B. Phillipp	12
19 May 1911	Hillsborough Co.	—	O. E. Baynard	24
27 Apr. 1913	Lee Co.	—	O. E. Baynard	3,9
27 Apr. 1913	Roco Bay, Pinellas Co.	large colony in trees	O. E. Baynard	8

(APPENDIX 1 CONTINUED)

Date	Location	Estimated Numbers; Remarks	Observer	Museum* of record
15 May 1918	Tampa Bay	—	J. L. Vaughn	4
20 Apr. 1920	Tampa Bay	—	—	3
17 May 1921	Tampa Bay	—	J. L. Vaughn	2,20
17 May 1921	Tampa Bay	—	W. F. Lewis	8
27 May 1921	Tampa Bay	—	J. L. Vaughn	23
28 Dec. 1921	Pelican Is.	—	T. D. Burleigh	10
20 Apr. 1926	Pinellas Co.	—	C. E. Doe	16
1 June 1926	Merritt Is.	—	K. Squires	2
10 June 1929	Merritt Is.	2,500 pairs	J. C. Howell, Jr.	12
28 Mar. 1930	Lee Co.	—	C. E. Doe	16
25 Apr. 1930	Near Bokelia?	—	C. E. Doe	16
10 Apr. 1931	Mosquito Lagoon, Brevard Co.	2,000± nests	W. H. Nicholson	23
6 June 1931	Pine Is. Res., Bird Key	—	R. W. Williams	13
7 June 1931	Matlacha Pass Res., 6-mi. Is.	—	R. W. Williams	13
3 May 1932	Bird Key, Hillsborough Co.	—	R. E. Gammell	7
22 Apr. 1934	Rattlesnake Key, Levy Co.	—	C. E. Doe	16
9 Mar. 1950	Is., n. side of Cocoa—Cocoa Beach	375 nests	C. E. Carter	15
10 Mar. 1953	Merritt Is.	—	H. Brandt	10
Georgia				
16 June 1898	Chatham Co.	on beach	T. D. Perry	1,16
South Carolina				
10 May 1901	Bird Bank, Bull's Bay	—	M. T. Cleckley	9
20 June 1901	Near Charleston	on beach	—	3
23 June 1901	Bay Point, near Beaufort	"large colony"	M. T. Cleckley	3
23 May 1915	Bird Bank, Bull's Bay	—	A. C. Bent	13
18 June 1915	Bird Bank, Bull's Bay	—	A. Sprunt, Jr.	30
7 July 1916	Bull's Bay	—	M. T. Cleckley	28
3 June 1925	Bull's Bay	—	W. B. Savary	5
14 June 1934	Georgetown Co.	—	H. L. Harllee	14
20 June 1942	Bull's Bay	—	E. J. DeCamps	14
10 June 1943	St. Helens Sound, Beaufort (Bird Bank)	—	E. J. DeCamps	4
10 July 1943	18 mi. e. Beaufort	—	E. J. DeCamps	14
Cuba				
8 Sep. 1930	Cacachita Bay	—	P. Bartsch	13

* Museums and collections are numbered as follows: 1. Calif. Acad. Sci., San Francisco; 2. Mus. Vert. Zool., Univ. Calif., Berkeley; 3. Western Found. Vert. Zool., Los Angeles, Calif.; 4. San Bernardino Co. Mus., San Bernardino, Calif.; 5. S. B. Peyton, private collection, Fillmore, Calif.; 6. Oakland Publ. Mus., Oakland, Calif.; 7. Santa Barbara Mus. Nat. Hist., Santa Barbara.

Calif.; 8. San Diego Mus. Nat. Hist., San Diego, Calif.; 9. Denver Mus. Nat. Hist., Denver, Colo.; 10. Carnegie Mus., Pittsburgh, Pa.; 11. Philadelphia Acad. Sci., Philadelphia, Pa.; 12. Amer. Mus. Nat. Hist., New York, N.Y.; 13. U.S. Natl. Mus., Wash., D.C.; 14. Zoological Mus., Clemson Univ., Clemson, S.C.; 15. C. E. Carter, private collection, Orlando, Fla.; 16. Fla. State Mus., Gainesville; 17. L.S.U. Mus. Nat. Sci., Baton Rouge, La.; 18. T. C. Meitzen, private collection, Refugio, Tex.; 19. R. W. Quillan, private collection, San Antonio, Tex.; 20. Univ. Kans. Mus. Nat. Hist., Lawrence; 21. Univ. Nebr. Zool. Dept. Mus., Lincoln; 22. Cleveland Nat. Sci. Mus., Cleveland, Ohio; 23. Royal Ont. Mus., Toronto; 24. Joseph Moore Mus., Earlham Coll., Richmond, Ind.; 25. Ohio State Mus., Ohio State Univ., Columbus; 26. Univ. Mich. Mus. Zool., Ann Arbor; 27. James Ford Bell Mus. Nat. Hist., Univ. Minn., Mpls.; 28. M. Pollock, private collection, Edmonton, Alta.; 29. Burke Memorial Mus., Univ. Wash., Seattle; 30. Puget Sound Mus. Nat. Hist., Univ. Puget Sound, Tacoma; 31. Zoology Mus., Ore. State Univ., Corvallis.

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SCIENCE

Chlorinated Hydrocarbons and Eggshell Changes in Raptorial and Fish-Eating Birds

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Chlorinated Hydrocarbons and Eggshell Changes in Raptorial and Fish-Eating Birds

Abstract. *Catastrophic declines of three raptorial species in the United States have been accompanied by decreases in eggshell thickness that began in 1947, have amounted to 19 percent or more, and were identical to phenomena reported in Britain. In 1967, shell thickness in herring gull eggs from five states decreased with increases in chlorinated hydrocarbon residues.*

New perspectives on the role of chlorinated hydrocarbon insecticides in our environment have come into focus in recent years. Successive discoveries have demonstrated that these compounds are systematically concentrated in the upper trophic layers of animal pyramids (*1*). Raptorial bird populations have simultaneously suffered severe population crashes in the United States and Western Europe (*2, 3, 4*). These involve reproductive failures which, at least in Britain, are characterized by changes in calcium metabolism and by a decrease in eggshell thickness resulting in the parent birds' breaking and eating their own eggs (*4, 5, 6*). Such a derangement of calcium metabolism or mobilization perhaps could result from breakdown of steroids by hepatic microsomal enzymes induced by exposure to low dietary levels of chlorinated hydrocarbons (*7*).

We have examined the possibility that the eggshell changes reported in Britain (*6*) have also occurred in the United States and that the raptor population crashes in Europe and North America may have had a common physiological mechanism. The population changes are without parallel in the recent history of bird populations (*8*). They include the pending extirpation of the peregrine falcon (*Falco peregrinus*) in northwestern Europe, the complete extirpation of the nesting population of this species in the eastern half of the United States, and simultaneous declines among other bird- and fish-eating raptors on both sides of the Atlantic.

We examined 1729 blown eggs in 39 museum and private collections. Shells were weighed to the nearest hundredth of a gram. In 29 percent of these, we were able to insert a micrometer through the hole drilled by the collector at the girth of the shell and to take four measurements of thickness 7 mm from the edge of the blow hole; these were then averaged to the nearest 0.01 mm for each shell. Thickness in each case then represented the shell itself plus the dried egg membranes. Peregrine falcons, bald eagles (*Haliaeetus leucocephalus*), and ospreys (*Pandion haliaetus*) were selected as having one or more regionally declining populations; golden eagles (*Aquila chrysaeetos*), red-tailed hawks (*Buteo jamaicensis*), and great horned owls (*Bubo virginianus*) were selected as representative of reasonably stationary populations that may be slowly declining as their habitats are gradually destroyed by man, but for which widespread reproductive failures are currently unknown. In addition, 57 eggs of the herring gull (*Larus argentatus*) were collected from five colonies in 1967. The shells of these were dried at room temperature for 4 months before being measured, and residues of the entire egg contents were analyzed by the Wisconsin Alumni Research Foundation for chlorinated hydrocarbons but not for polychlorinated biphenyls. Analytical procedure followed that outlined by the U.S. Food and Drug Administration (*9*). Analyses were conducted on chromatograph (Barber Coleman, GC 5000, and Jarrell-Ash, mode 700) with electron-capture dete The glass column (0.6 cm by 1.2 m packed with 5 percent DC 200 (1 2 on Cromport XXX. The column perature was 210°C, and the nit flow rate was 75 cm³/min. Each tion of the ground and dried sa was extracted for 8 hours or more Soxhlet apparatus with a mixtu ether and petroleum ether (70: Portions of the extracts were fu purified by putting them throu Florisil column.

In California, where the pere falcon population is in "a serious dition" (*10*), a change of 18.8 pe in shell weight occurred from 19 1952. Ratcliffe (*6*) found a corres ing decrease of 18.9 percent in Br The change in California involved crease in shell thickness and ha precedent in the previous 57-yea corded history of the peregrine in state (Fig. 1). In the eastern U States, where the nesting populatic peregrines has now been wiped ou fragmentary data indicate that the change took place (Table 1). Br

Table 1. Weights of raptor eggshells in museum and private collections. Citations (2 refer to the data for the population trend; S.E., standard error of the mean.

Region	Period	No.	Weight (g)		Popu tren repr ti
			Mean ± S.E.	Change (%)	
		Red-tailed hawk			
Calif. (*23*)	1885–1937	386	6.32 ± 0.032		
	1943–44	6	6.09 ± 0.237	− 3.6	Stati
	1953–67	8	6.49 ± 0.214	+ 2.7	Stati
		Golden eagle			
Calif. (*23*)	1889–1939	278	13.03 ± 0.083		
	1940–46	28	12.70 ± 0.161	− 2.5	Stati
	1947–65	33	13.41 ± 0.232	+ 2.9	Stati
		Bald eagle (24a)			
Brevard Co., Fla.	1886–1939	56	12.15 ± 0.127		
	1947–62	12	9.96 ± 0.280	− 18.0	Decl
Osceola Co., Fla.	1901–44	25	12.32 ± 0.240		
	1959–62	8	9.88 ± 0.140	− 19.8	Decl
		Osprey (24b)			
Md.-Va.	1890–1938	152	7.05 ± 0.054		
	1940–46	21	6.91 ± 0.164	− 2.0	Stati
	1955	3	6.85	− 2.8	Stati
N.J.	1880–1938	117	7.08 ± 0.069		
	1957	6	5.30 ± 0.446	− 25.1	Decl
		Peregrine (25)			
B.C.	1915–37	[illegible]	4.24 ± 0.061		
	1947–53	15	4.18 ± 0.081	− 1.4	Stati
Calif. (*23*)	1895–1939	235	4.20 ± 0.031		
	1940–46	49	4.07 ± 0.038	− 3.1	No
	1947–52	31	3.41 ± 0.084	− 18.8	Decl
N.H. to N.J.*	1888–1932	56	4.38 ± 0.034		
Vt.	1946	3	4.30	− 1.8	Stati
Mass.	1947	3	3.47	− 20.8	Exti
N.J.	1950	3	3.24	− 26.0	Exti
		Great horned owl			
Calif. (*23*)	1886–1936	154	4.50 ± 0.033		
	1948–50	12	4.62 ± 0.119	+ 2.4	Stati

* Including Vermont and Massachusetts.

eggshells in a North American peregrine eyrie were observed for the first time in 1947 by J. A. Hagar 60 miles (9.6 km) from the Massachusetts eyrie cited in this table (*11*). They were next inferred in Quebec in 1948 when egg-eating was observed at the same site in 1949 (*12*), and were observed in Pennsylvania in 1949 and 1950 (*13*). Chlorinated hydrocarbon data for this now-extinct regional population are completely absent. For nine surviving adult peregrines in Canada's Northwest Territories in 1966, the data are reported to have averaged 369 parts per million (ppm) (fresh weight) in fat (*14*). For four adults in another migratory population in northern Alaska, values were even higher (*15*).

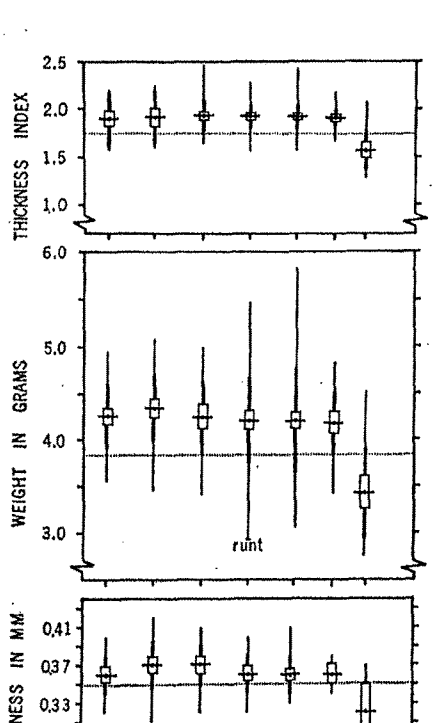

Fig. 1. Measurements of 614 California peregrine eggshells collected since 1891. The dotted horizontal line is the midpoint between the 95 percent confidence limits for 1947–52 and the lowest of any preceding group. Solid horizontal bars are means; rectangles, 95 percent confidence limits; heavy vertical lines, standard deviations; narrow vertical lines, range in sample. The thickness index, calculated as ten times the weight divided by the product of the length and breadth (in mm) of each egg, was devised by Ratcliffe (*6*) for the study of museum eggs and appears here to be a meaningful statistic. The sizes of samples for measurement of weight and of thickness index for the periods were 71, 49, 36, 85, 155, 30, and 31, respectively; and the sizes of the samples for measurement of thickness were 24, 31, 29, 23, 37, 7, and 6.

For the five other raptorial species we have studied, the data do not permit a precise delineation of the onset of the change in calcium metabolism or mobilization, but the decrease (Table 1) in shell weight (and hence thickness) has involved only declining populations and not stationary ones. Change in shell thickness occurs in poultry as a result of dietary deficiencies and age (*16*, *17*). This phenomenon would probably not occur simultaneously on two continents 1 year after the chlorinated hydrocarbon insecticides came into general usage. Other chemicals affect shell thickness in poultry (*17*), but the finding of high concentrations of chlorinated hydrocarbons in the eggs of wild populations of raptors and the time correlation of shell changes with the introduction of DDT [1,1,1-trichloro-2,2-bis (*p*-chlorophenyl) ethane] tend strongly to suggest that chlorinated hydrocarbons are the major contributing cause, although it is not unlikely that other chemicals could be contributory.

In order to test the hypothesis that these recent changes of thickness in raptor eggshells were the result of differences in exposure to chlorinated hydrocarbons we analyzed 10 to 14 eggs taken in 1967 from each of five colonies of the herring gull (*Larus argentatus*). Mean shell weight and thickness in 55 eggs collected in the same five states prior to 1947 disclosed no geographic gradients or significant differences. The 1967 mean thicknesses for each colony were therefore compared to mean levels of residual DDE [1,1-dichloro-2,2-bis (*p*-chlorophenyl) ethylene] on a fresh-weight basis, with the result shown in Fig. 2, the *r* value being significant, with $P = .001$. The residues of polychlorinated biphenyls (*18*) have not been studied in these ecosystems, but DDE has been consistently high in the Lake Michigan birds, averaging (fresh weight) 1925 ppm (S.E. 274) in the fat of 12 healthy adults collected in 1963–64 (*19*).

Reproduction in these gull colonies was generally normal in 1967 except perhaps in Wisconsin. At the latter colony where an 11 percent mean decrease in shell thickness occurred, some egg breakage and shell flaking was evident in 1967, although not at the frequency seen in previous years. Excessive reproductive failure occurred at this site in 1964 when about 18 percent of the eggs lost about one-third of the shell due to flaking, when clutch size decreased and embryonic mortality was high, and when DDE residues averaged

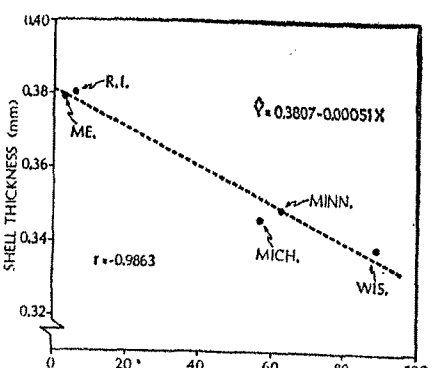

Fig. 2. Variation in shell thickness and DDE concentrations in the eggs of herring gulls in 1967. The eggs were taken off Block Island, R.I.; Green Island in Penobscot Bay, Me.; Rogers City, Mich., on Lake Huron; near Knife River, Minn., on Lake Superior; and the Sister Islands in Green Bay, Wis. Some polychlorinated biphenyls probably occurred in these eggs, but they have not yet been identified.

202 ppm (S.E. 34) in nine eggs (*20*). (If linear extrapolation of the 1967 values is carried out to 202 ppm, the shell thickness in 1964 could be estimated as having decreased by about 32 percent.) The effectiveness of DDE in the enzymatic metabolism of aminopyrine has been reported by Hart and Fouts (*21*), and our data suggest that this compound, because of its prevalence, has played a major role in inducing the hepatic microsomal metabolism of steroids that in turn resulted in the eggshell changes we have encountered in museum collections. Without doubt DDE is the commonest insecticide or insecticide analog now being found in avian tissues (*22*). In 1966, it was found to average 284 ppm (S.E. 62) in the fat of nine arctic-breeding peregrine falcons (*14*) and about 414 ppm in four others on a wet-weight basis (*15*). Concentrations of this compound and other chlorinated hydrocarbons in the peregrine populations that crashed farther south can be assumed to have been as high—and they may have been much higher.

From the above evidence and that accumulated by others (*2*, *4*, *6*, *8*), we have reached these conclusions: (i) many of the recent and spectacular raptor population crashes in both the United States and Western Europe have had a common physiological basis; (ii) eggshell breakage has been widespread but largely overlooked in North America; (iii) significant decreases in shell thickness and weight are characteristic of the unprecedented reproductive failures of raptor populations in certain

parts of the United States; (iv) the onset of the calcium change 1 year after the introduction of chlorinated hydrocarbons into general usage was not a random circumstance; and (v) these persisting compounds are having a serious insidious effect on certain species of birds at the tops of contaminated ecosystems.

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25. Except for the California data (*23*) the data on population trends are given in (*8*) by F. L. Beebe for British Columbia; by W. R. Spofford for Vermont; by J. A. Hagar for Massachusetts; and by D. D. Berger *et al.* for New Jersey.
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TITLE OF THESIS CHLORINATED HYDROCARBONS: THEIR DYNAMICS AND EGGSHELL EFFECTS ON HERRING GULLS AND OTHER SPECIES

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Publications ~~See Attached List.~~

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Date 13 August 1970

Signed Joseph J. Hickey
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