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# Polychlorinated Biphenyls and Chlorinated Insecticides in Plasma of Caspian Terns: Relationships with Age, Productivity, and Colony Site Tenacity in the Great Lakes

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**Abstract.** Chlorinated hydrocarbons such as polychlorinated biphenyls (PCBs) and chlorinated insecticides have often been detected in Great Lakes fish-eating birds at concentrations that are correlated with greater than expected embryo mortality and reduced reproductive success. Blood from 111 known-age, adult Caspian terns (*Sterna caspia*) nesting in several regions of the upper Great Lakes was collected in 1990 to examine bioavailability of PCBs, to compare concentrations of PCBs among nesting locations, and to determine relationships between concentrations of PCBs and age, productivity, and colony site tenacity. PCBs, DDE, dieldrin, and trans-nonachlor were detected in all the samples. Concentrations of PCBs were, on average, 10, 100, and 250 times greater than those of DDE, dieldrin, and trans-nonachlor, respectively. Concentrations of PCBs were not correlated with age, and were greater in Caspian terns from Saginaw and Green Bays than in Caspian terns from the North Channel and Georgian Bay. Concentrations of PCBs and DDE were significantly correlated with one-another and their accumulation patterns were the most similar among all the chemicals studied. Patterns of organochlorines as determined by cluster analysis were most similar for the nearest nesting locations. The bioaccumulation of PCBs in Great Lakes Caspian terns appeared to be seasonal and did not vary with adult age. A significant negative correlation was observed between mean concentrations of PCBs by region and percent terns returning to natal region. Those populations which were likely to be affected by PCBs were those nesting in Green Bay and Saginaw Bay.

A problem of continuing concern in the Great Lakes is the frequently observed pollutant-related effects on reproduction of fish-eating birds. Most of the effects have been attributed to synthetic halogenated hydrocarbons (SHHs). Of the SHHs which are known to exist in these birds, concentrations of polychlorinated biphenyls (PCBs) and planar halogenated hydrocarbons (PHHs) have often been associated with reproductive impairment characterized by increased embryo mortality, edema, congenital deformities of chicks and behavioral abnormalities of adult birds (Kubiak *et al.* 1989, Gilbertson *et al.* 1991, Ludwig *et al.* in press). Abnormalities and reproductive impairment have been documented in herring gulls (*Larus argentatus*), double-crested cormorants (*Phalacrocorax auritus*), Forster's terns (*Sterna forsteri*), and Caspian terns (*Sterna caspia*, Gilbertson *et al.* 1976; Mineau *et al.* 1984; Heinz *et al.* 1985; Hoffman *et al.* 1987; Kubiak *et al.* 1989; Fox *et al.* 1991; Ludwig *et al.* in press). Synthetic, halogenated hydrocarbons such as PCBs, polychlorinated dibenzo-dioxins (PCDDs), and other aryl hydrocarbon hydroxylase (AHH) inducers were directly linked with embryotoxic effects, impaired reproductive success, nest abandonment, and other behavioral abnormalities in Forster's terns from Green Bay (Hoffman *et al.* 1987; Kubiak *et al.* 1989). It has been suggested that migratory birds of the Great Lakes may receive a large proportion of their exposure during migration or in wintering areas. The source of contaminants is an important issue relative to remedial action planning. If migratory colonial birds of the Great Lakes are exposed to significant concentrations of SHHs in their wintering areas, remediation of local areas may not have much effect on the concentrations of SHHs in the birds or their eggs and thus not significantly improve reproductive success.

The herring gull has been used to monitor the status and trends of concentrations of environmental contaminants in the Great Lakes since 1971 (Bishop and Weseloh 1990). However, very few studies have investigated the concentrations or potential effects on Great Lakes Caspian terns (Struger and Weseloh 1985; Tillitt *et al.* 1991; Yamashita *et al.* in press). The Caspian tern has been listed as threatened in the state of Michigan since 1978 (Ludwig 1979). Studies on their reproductive biology and other field observations have suggested that Caspian terns (CTs) may be very sensitive to exposure to current concentrations of SHHs (Ludwig 1965, 1979; Shugart *et al.* 1978; Ludwig *et al.* in press). Concentrations of PCBs and DDT [1,1,1-trichloro-2,2-bis(*p*-chlorophenyl) ethane] have decreased from the maximum concentrations which were observed in bird eggs of the Great Lakes in the 1970s. However, concentrations now seem to be decreasing only slowly. Thus, to understand the

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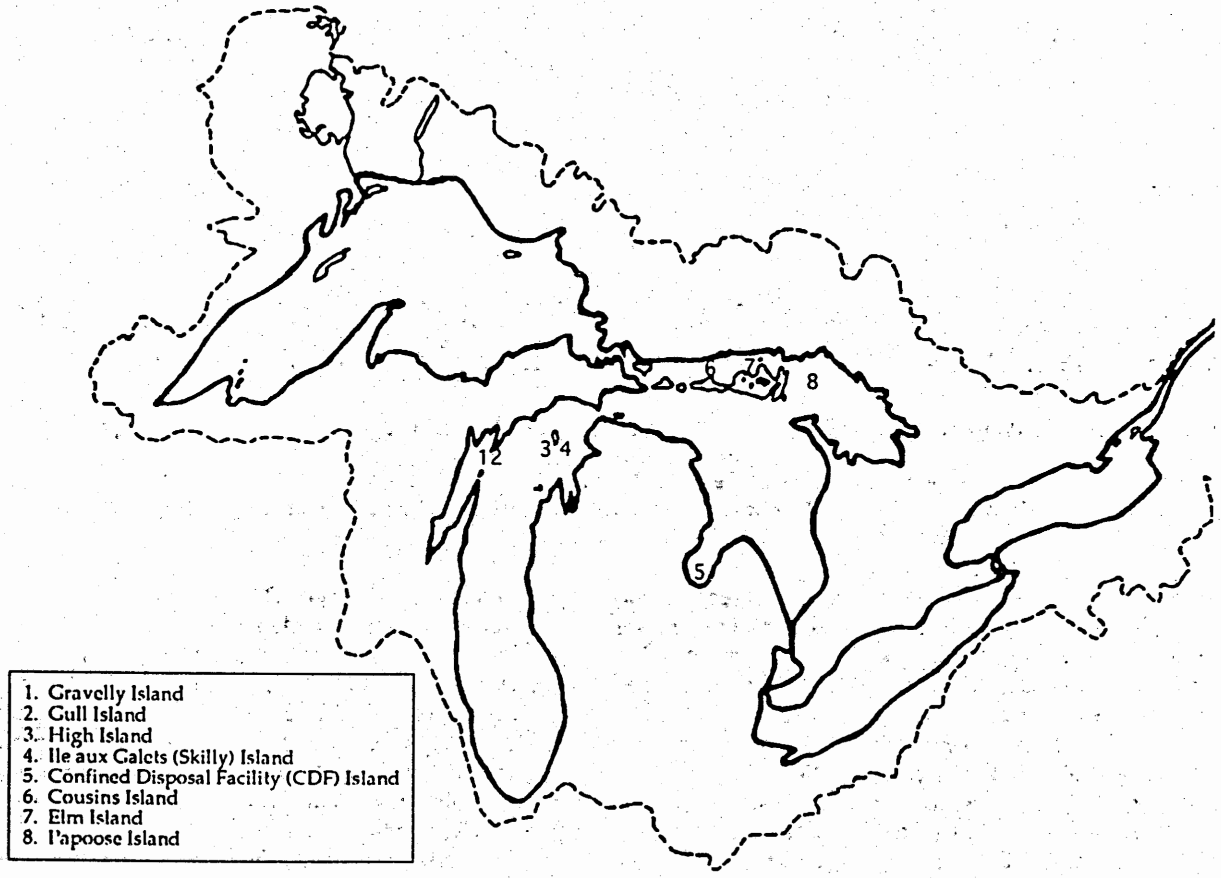


**Fig. 1.** Map of the Great Lakes showing Caspian tern nesting locations sampled in 1990

dynamics of bird populations of the Great Lakes we need to assess the background contamination by these compounds.

Caspian terns nest in dense colonies on islands with sand, gravel, and sparsely vegetated areas in the Great Lakes (Ludwig 1965). Most CTs nest in a geographic band of approximately 160 × 400 km from the northern third of Green Bay across northern Lake Michigan, through the Canadian North Channel of Lake Huron, to central and northeastern Georgian Bay, but two colonies exist in Lake Ontario and there is a major colony at the confined disposal facility (CDF) in inner Saginaw Bay (L'Arrivee and Blokpoel 1988; Struger and Weseloh 1985). In the Great Lakes, Caspian tern chicks were banded every year from 1922 to 1941, sporadically 1943–1958, and almost annually 1959–1990 (Ludwig 1965, 1979, unpublished data). Thus, the opportunity existed to recapture banded known-age individuals to collect blood for the analysis of chlorinated hydrocarbons.

The use of blood plasma for monitoring chlorinated hydrocarbons (CHs) in wild birds allows for repeated sampling of the same individuals. Concentrations of CHs in plasma can also be used to estimate concentrations in other body compartments. Good correlations between concentrations of CHs in serum and plasma and concentrations in fat tissue have been observed in mallards (*Anas plathyrhynchos*, Friend *et al.* 1979), raptors (Henny and Meeker 1981), and white-faced ibis (*Eudocimus albus*, Capen and Leiker 1979). The objectives of our study were to determine the status and trends of concentrations of CHs in known-age CTs, to compare concentrations of PCBs among islands and regions, and to determine whether concentrations of PCBs were correlated with age or colony site tenacity. Additionally, we assessed productivity of CTs and estimated rates of abnormalities.

## Materials and Methods

### *Study Areas*

Nesting CTs were captured during 4–11 June 1990 with a cannon net at eight colonies from five regions in the upper Great Lakes: Gull and Gravelly islands at Green Bay, High and Ile Aux Galet at northern Lake Michigan, confined disposal facility (CDF) at Saginaw Bay, Elm and Cousins islands at the North Channel, and Papoose island at Georgian Bay Lake Huron (Figure 1). The cannon-netting was limited to days with no rain, little wind, and favorable temperatures to protect the eggs and chicks from overexposure and to minimize disturbance of the nesting colony. At each colony the cannon net was set up on the border of a nesting site and oriented so that the wind could be used to assist in deploying the net.

A total of 653 adult CTs was captured and banded; 136 of which had been previously banded. Approximately 6 ml of blood were obtained from the brachial vein of 111 adults which had been banded previously. Sixty-nine individual and five pooled samples of plasma were used for the analysis of CHs. Blood was collected with a heparinized syringe, transferred into heparinized vacutainer tubes (Becton Dickinson Vacutainer Systems, Rutherford, New Jersey), and centrifuged for 10 min at 3000 rpm within 6 h of the time of collection. The plasma was stored at −4°C until chemical analysis.

Table 1. Colony size, hatching success, and productivity of upper Great Lakes Caspian terns, 1990[a]

| Region/colony | Nests | Clutch size | Hatching success (percent eggs hatched) | Fledging success (young fledged/nest) |
|---|---|---|---|---|
| North Channel, LH | | | | |
| Elm | 206 | 2.21 | 81 | NA[b] |
| Cousins | 485 | 2.19 | 82 | NA |
| Georgian Bay, LH | | | | |
| Papoose | 199 | 2.14 | NA | NA |
| Saginaw Bay, LH | | | | |
| CDF | 223 | 2.15 | 75 | 1.06 |
| Northern Lake Michigan | | | | |
| High Island | 878 | 2.12 | 74 | 1.08 |
| Green Bay, LM | | | | |
| Gull and Gravelly Islands | 906 | 2.26 | 76 | 0.94 |

[a] First nesting attempts
[b] Not assessed

### *Assessment of Productivity*

To assess productivity, we visited the colonies two or three times during the breeding season to collect information on number of eggs laid, hatching and fledging success. CTs arrived in the Great Lakes in late April and early May and started laying between May 5 and 15 depending on local weather conditions. Incubation lasted approximately 26 days and fledging occurred at about 40 d after hatch.

### *Chemical Analysis*

Chlorinated hydrocarbons were extracted by the method of Burse *et al.* (1990), except that only 1 g of plasma was used for the analysis. The combined hexane-ether extracts were concentrated to 0.5 ml, without keeper solution, in a rotary evaporator. Cleanup procedures followed those described by Ribick *et al.* (1982) with 35 ml and 40 ml eluant mixture volumes. The eluate volumes were concentrated almost to dryness in a rotary evaporator, resuspended to 1 ml with isooctane, and spiked with 50 μl of PCB #30 (11.4 ng/ml) as internal standard for GC analysis.

Concentrations of individual CHs were quantitated with a Perkin Elmer 8500 gas chromatograph, with a $^{63}$Ni electron capture detector, and a fused silica capillary column DB-5 (J&W Scientific), 30 m × 0.25 mm i.d., 0.25 μm film thickness. The injector was operated in the splitless mode. The carrier gas was helium delivered at 1 ml/min and the makeup gas was nitrogen delivered at 59 ml/min. The injector and detector temperatures were 230°C, and 350°C, respectively. Two column temperature gradient programs were used: program one for the analysis of most CHs started at 120°C for 3 min with ramp rates of 30°C/min to 150°C, hold for 5 min, 4°C/min to 225°C, hold for 10 min, 20°C/min to 280°C, hold for 15 min, run time 56 min; program two for the analysis of PCBs, DDE [2,2-bis-(4-chlorophenyl)-1,1-dichloroethane] and hexachlorobenzene started at 120°C for 6 min, and ramp rates of 2°C/min to 260°C, and 20°C/min to 280°C, hold for 1 min, run time 78 min. A Perkin Elmer 8300 autosampler was used to inject the samples. The chromatographic data were transferred directly to a computer. Total concentrations of PCBs were calculated by the use of "COMSTAR," a linear regression software program, with outlier evaluation and elimination, developed at the University of Wisconsin Superior (Burkhard and Weininger 1987). The pattern of relative concentrations of individual PCB congeners was compared to a 1 : 1 : 1 : 1 mixture of Aroclors® 1242, 1248, 1254, and 1260. The limit of detection (LOD), estimated by the method of Taylor (1987), was 2.4 ng/g for all CHs, except for endrin and DDT which were 6 ng/g and 12.6 ng/g, respectively. Recoveries averaged 94% (range 88–97) for a mixture of pesticides and 101% (range 87–115) for total PCBs quantitated as a mixture of Aroclors® 1242, 1248, 1254, and 1260 (1 : 1 : 1 : 1). Recoveries of organochlorine pesticides and Aroclor® 1254 from reference material (spiked bovine serum from Michigan Department of Public Health) averaged 92% and 87%, respectively. Accuracy of our PCB laboratory standards was within 2% of the EPA certified Aroclor® standard values.

### *Statistical Analysis*

Only PCBs, DDE, dieldrin [1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-1,4-*endo*-5,8-*exo*-dimethanonaphthalene], and *trans*-nonachlor [1,2,3,4,5,6,7,8,8-nonachloro-2,3,3a,4,7,7a-hexahydro-4,7-methano-indene], which appeared in all 74 samples, were used for most of the statistical comparisons. *o,p'*-DDE was detected at concentrations equal to or less than 25 ng/g in a few samples; thus, values equal or greater than the LOD were added to *p,p'*-DDE values and are reported as total DDE. Similarly, *o,p'*-DDD, and *p,p'*-DDD [2,2-bis-(4-chlorophenyl)-1,1-dichloroethane] were detected at small concentrations in a few samples; values above LOD were added to *p,p'*-DDT values and are reported as total DDT. The concentrations of CHs were log-transformed before statistical analysis with linear methods. Analysis of variance (ANOVA) was used for comparisons of mean concentrations among locations and regions. The Tukey-Kramer method of multiple comparisons (Neter *et al.* 1985) was used for all pairwise comparison of means. Cluster analysis was used to determine associations and similarities in patterns of contaminants among locations or regions. The statistical analysis was performed with the computer software "SYSTAT: The system for statistics" (Wilkinson 1990).

## Results

### *Productivity*

Clutch size was similar for CTs nesting at five regions of the upper Great Lakes (Table 1). Hatching rates were also similar (74–82% of eggs laid) during the first nesting attempt. Productivity to near fledgling age (21 d) varied from 0.94 to 1.08 young/pair. The second nesting attempts at CDF, Saginaw Bay were less successful since approximately half of the older

**Table 2.** Developmental deformities and abnormalities in hatched Caspian tern chicks of the Michigan Great Lakes, 1986–1990

| | Number with deformities/abnormalities[a] | | | | |
|---|---|---|---|---|---|
| Region | Number inspected | Clubbed feet | Open abdomen/ gastroschisis | Scoliosis | Total |
| Green Bay, Lake Michigan | 4,075 | 4 (0.98) | 3 (0.74) | | 7 (1.72) |
| Northern Lake Michigan | 4,212 | 8 (1.90) | 1 (0.24) | 1(0.24) | 10 (2.37) |
| Saginaw Bay, Lake Huron | 1,064 | 3 (2.82) | 6 (5.64) | 1(0.94) | 10 (9.40) |

[a]Frequency per thousand in parentheses

**Table 3.** Concentrations (μg/g, wet wt) of chlorinated hydrocarbons in plasma of upper Great Lakes Caspian terns, 1990

| Region/Colony | N | PCBs | DDE | Dieldrin | t-Nonachlor | DDE:PCB |
|---|---|---|---|---|---|---|
| North Channel, L. Huron | | | | | | |
| Cousins Island | 5 | 0.910 | 0.124 | 0.016 | 0.008 | 0.136 |
| | | (0.381–2.168) | (0.048–0.320) | (0.007–0.032) | (0.004–0.019) | |
| Elm Island | 10 | 1.023 | 0.107 | 0.009 | 0.004 | 0.104 |
| | | (0.554–1.893) | (0.054–0.208) | (0.005–0.015) | (0.002–0.006) | |
| Total | 15 | 0.984 | 0.112 | 0.011 | 0.005 | 0.114 |
| | | (0.645–1.500) | (0.071–0.178) | (0.007–0.015) | (0.003–0.007) | |
| Georgian Bay, L. Huron | | | | | | |
| Papoose Island | 10 | 1.396 | 0.182 | 0.015 | 0.006 | 0.130 |
| | | (0.833–2.340) | (0.103–0.319) | (0.010–0.023) | (0.004–0.001) | |
| Northern Lake Michigan | | | | | | |
| High Island | 14 | 1.671 | 0.167 | 0.022 | 0.008 | 0.100 |
| | | (0.994–2.810) | (0.094–0.294) | (0.014–0.034) | (0.005–0.012) | |
| Isle Aux Galet | 15 | 2.143 | 0.205 | 0.025 | 0.009 | 0.096 |
| | | (1.297–3.538) | (0.118–0.354) | (0.016–0.038) | (0.006–0.015) | |
| Total | 29 | 1.901 | 0.185 | 0.023 | 0.008 | 0.097 |
| | | (1.403–2.574) | (0.133–0.258) | (0.018–0.030) | (0.006–0.011) | |
| Saginaw Bay, L. Huron | | | | | | |
| CDF | 15 | 2.512 | 0.213 | 0.017 | 0.007 | 0.085 |
| | | (1.647–3.829) | (0.134–0.337) | (0.012–0.024) | (0.005–0.010) | |
| Green Bay, L. Michigan | | | | | | |
| Gull Island | 2 | 3.499 | 0.281 | 0.023 | 0.013 | 0.080 |
| | | (0.884–13.823) | (0.063–1.258) | (0.007–0.074) | (0.003–0.046) | |
| Gravelly Island | 3 | 3.236 | 0.198 | 0.014 | 0.006 | 0.061 |
| | | (1.053–9.936) | (0.058–0.673) | (0.005–0.035) | (0.002–0.017) | |
| Total | 5 | 3.334 | 0.228 | 0.017 | 0.008 | 0.068 |
| | | (1.607–6.928) | (0.102–0.505) | (0.009–0.031) | (0.004–0.016) | |

[a]Geometric means and 95% confidence intervals (in parentheses). Samples from Gull and Gravelly Islands were pools of two and three individuals each (five individual samples from Gull and seven from gravelly Islands).

chicks died between 10 and 25 d of age possibly with wasting syndrome (Ludwig *et al.* in press). Although we did not check the status of second clutches or second nesting attempts thoroughly at other colonies, only the second clutch chicks of Saginaw Bay exhibited these symptoms.

### *Developmental Deformities and Abnormalities*

A total of 9,351 chicks were inspected for deformities/abnormalities over four U.S. colonies during 1986–1990. Clubbed feet, and gastroschisis (open abdomen) were the most common defects observed (Table 2). The incidence of abnormalities and deformities was much greater in Saginaw Bay than at other nesting areas, and almost two orders of magnitude above abnormality rates recorded when banding a similar number of chicks between 1962 and 1971 (Ludwig *et al.* in press).

### *Concentrations and Occurrence of Chlorinated Hydrocarbons*

Polychlorinated biphenyls, DDE, and dieldrin were detected in all samples of plasma while *trans*-nonachlor was detected in 97% (Table 3). Other CHs were detected in fewer samples at lesser concentrations: Alpha-chlordane [1,2,4,5,6,7,8,8-octachloro-2,3,3a,4,7,7a-hexahydro-4,7-methanoindene] in 72% (N = 53, mean = 0.004 μg/g), HCB in 46% (N = 34, mean = 0.005 μg/g), and DDT in 31% (N = 23, mean = 0.022 μg/g).

**Table 4.** Tukey-Kramer HSD comparisons of mean concentrations of chlorinated hydrocarbons[a]

| Region | PCBs | DDE | Dieldrin | t-Nonachlor |
|---|---|---|---|---|
| North Channel, Canadian Lake Huron | A | A | A | A |
| Georgian Bay, Canadian Lake Huron | A B | A B | A | A B |
| Beaver Islands, Northern Lake Michigan | B C | B | B | B |
| Saginaw Bay, Lake Huron | C | B | B | A B |
| Green Bay, Lake Michigan | C | B | A B | A B |

[a]Means not sharing the same letter are significantly different

Total concentrations of PCBs were approximately 10 times greater than DDE and 100 to 250 times greater than other CHs. Concentrations of PCBs in plasma were significantly different among nesting locations ($P < 0.001$) and among regions ($P < 0.001$, Tables 3 and 4). Concentrations of PCBs were greater in plasma of CTs from Green Bay (Gull and Gravelly) islands and the Saginaw Bay CDF ($P < 0.001$), and were lesser in terns from the North Channel (Cousins and Elm) islands. Concentrations of PCBs in CTs from northern Lake Michigan (High and Ile Aux Galet) islands were intermediate between those of Green Bay and the North Channel colonies.

Concentrations of DDE in CTs were also significantly different among colonies ($P < 0.05$) and among regions ($P < 0.001$). Concentrations of DDE were significantly greater ($P < 0.001$) in CTs from Saginaw Bay, Green Bay, and northern Lake Michigan than in CTs from the North Channel. Concentrations of DDE, however, were not significantly different between the North Channel and Georgian Bay regions. Concentrations of PCBs and DDE in plasma of CTs covaried and were significantly correlated ($r^2 = 0.63$, $P < 0.001$). DDE : PCB ratios varied from 0.068 in Green Bay to 0.130 in Georgian Bay (Table 3).

Concentrations of dieldrin were also significantly different among CT colonies ($P < 0.001$) and among regions ($P < 0.001$). Concentrations of dieldrin were greater in CTs from Saginaw Bay (CDF) and northern Lake Michigan (High and Ile Aux Galet) and were lesser at the North Channel (Elm Island). Overall, concentrations of PCBs, DDE, and dieldrin were not significantly different between islands within each of three regions where more than one island was sampled. Trans-nonachlor concentrations in CTs were relatively low and were significantly different only between the North Channel and northern Like Michigan ($P < 0.05$).

### *Patterns of Relative Concentrations of Chlorinated Hydrocarbons Among Regions*

The similarities and associations in patterns of relative concentrations of chlorinated hydrocarbons among nesting locations and regions were investigated by use of single-linkage, cluster analysis. The nesting locations with the greatest similarity in patterns of contaminants were also those that were geographically most near (Figure 2a). Patterns of contaminants in CTs from Cousins and Elm islands (North Channel) were similar as were the patterns from Gull and Gravelly islands (Green Bay). Patterns of CHs in CTs from High and Ile Aux Galet islands (northern Lake Michigan) that were intermediate in concentrations of CHs tended to cluster with both lesser (Papoose, Georgian Bay) and greater (CDF, Saginaw Bay) contaminated sites respectively.

The similarities and associations of concentrations of CHs in plasma of CTs are more clear when regions instead of individual locations are compared. The North Channel and Georgian Bay at the Canadian Lake Huron were the two regions where CTs were least contaminated and had similar contaminant patterns (Figure 2b). Colonies from northern Lake Michigan were the next least contaminated and were added to the cluster next, followed by the more contaminated Saginaw Bay and Green Bay colonies which joined the cluster at greater Euclidean distances.

### *Polychlorinated Biphenyls and DDE Relationships with Age*

Forty-five of the 111 adult CTs collected for plasma analysis had been banded as chicks. The median age at time of recapture was 12 (range 4–29) yr (Figure 3). Correlations between concentrations of PCBs or DDE and age were not statistically significant, which indicates that the accumulation of CHs was not age-related (Figure 4).

### *Relationships Between PCBs and Colony Site Tenacity*

The locations where 82 banded terns were recovered up until May 1992 were obtained from the USFWS Bird Banding Laboratory, Laurel, MD. The total number of captured (banded) individuals and the number and percent individuals which had been banded previously at the same place, including both birds banded as adults and as chicks, indicate that site (region) tenacity was above 80% for all regions, except for Green Bay, where it was below 60% (Table 5). Moreover, natal region tenacity, defined as the proportion of returning adults formerly banded as chicks in the same region, decreased significantly along a gradient from the Canadian Lake Huron colonies to the U.S. colonies (Table 5). The number of CTs banded as chicks returning to their natal region was significantly less than expected (Chi-square = 13.85, 4 df, $P < 0.01$) at the three U.S. regions, with no significant difference from expected at the Canadian colonies (Table 5). Approximately 80% of the total number of banded CTs had been banded as chicks. Adults had been banded only every four years and less consistently than chicks. Compared to the total number of returning adults, only 20% of those which were banded as chicks were observed at the most contaminated colonies of Green Bay and Saginaw Bay. When only the proportion that were banded as chicks is considered, a significant, negative correlation ($r^2 = 0.83$, $P < 0.001$) was observed between mean concentrations of PCBs and the number of CTs returning to the natal region (Figure 5).

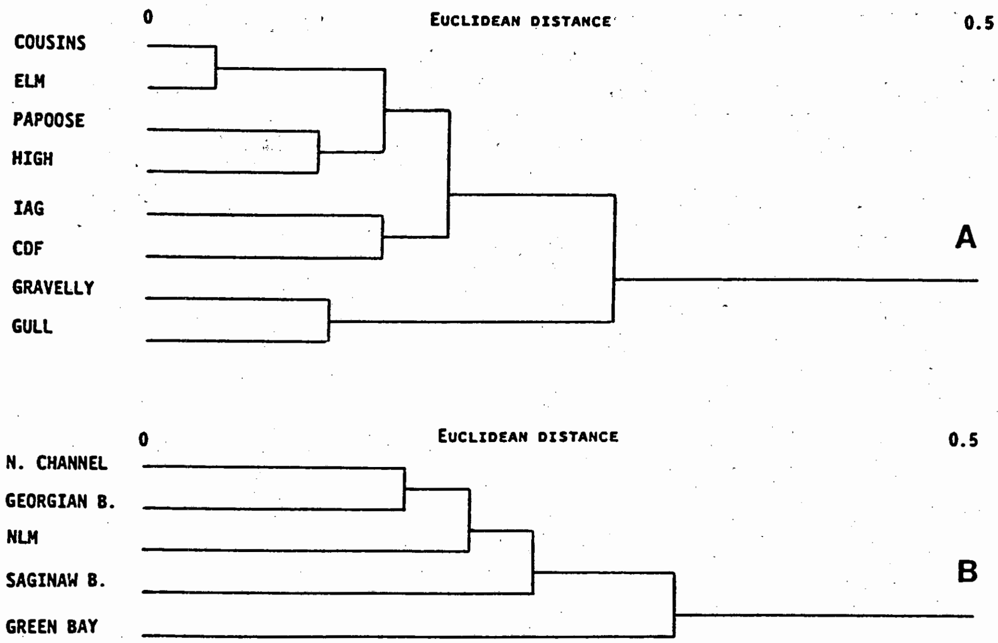


**Fig. 2.** Dendograms of upper Great Lakes Caspian tern colonies and regions clustered using geometric mean concentrations of 7 chlorinated hydrocarbons. Distance metric is Euclidean distance. Single-linkage method (nearest neighbor)

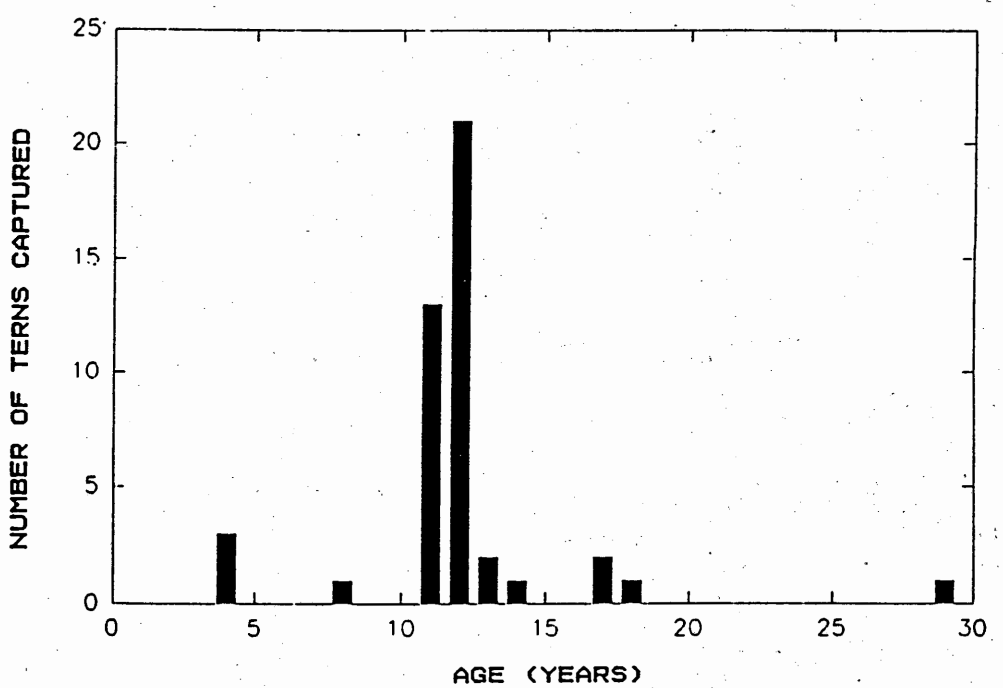


**Fig. 3.** Age distribution of Caspian terns captured for blood collection (only terns which were banded as chicks are included)

## Discussion

### *Productivity*

With some exceptions, productivity (*i.e.*, chick survival to 21 d of age) at five regions of the Great Lakes during 1990 was excellent with similar hatching rates from first nesting attempts in all colonies. We suspect that the causes of greater mortality of chicks and lesser hatching success of CTs from the Saginaw Bay CDF during the second nesting attempt might have been related to greater concentrations of PCBs or other contaminants. However, the success of second nesting attempts at other colonies was not checked. Food for CTs did not seem to be limited in the vicinity of the CDF in Saginaw Bay during this period since dropped and regurgitated fish were commonly observed. More acute episodes of wasting syndrome were noted in CTs from the Saginaw Bay CDF during 1987, 1988, and 1991 (Ludwig *et al.* in press). Except for the colony at the CDF, we did not observe wasting syndrome in chicks from other colonies. Hatching success of CTs was lesser for the Great Lakes colonies than for colonies nesting farther south in Texas which had 85% success (Mitchell and Custer 1986), and in Finland which had 85–95% hatching success (Soikkeli 1973).

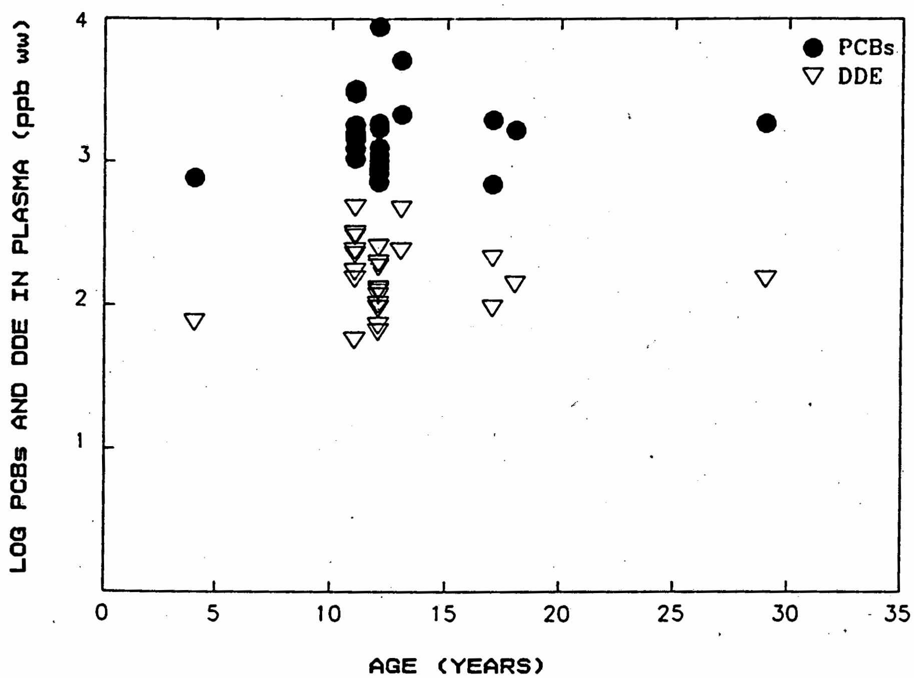


**Fig. 4.** Relationships between concentrations of PCBs and DDE with Caspian terns age

**Table 5.** Colony-site tenacity of Caspian terns recaptured for blood collection, 1990

| Region where banded | Terns captured | Number captured in same region[a] | Number banded as chicks and captured in same region[b] | |
|---|---|---|---|---|
| | | | Observed | Expected |
| Georgian Bay, Canadian Lake Huron | 7 | 7 (100) | 5 (71.4) | 5.6 |
| North Channel Canadian Lake Huron | 16 | 13 (81.2) | 9 (69.2) | 10.4 |
| Beaver Islands, Northern Lake Michigan | 26 | 23 (88.5) | 10 (43.5) | 18.4 |
| Saginaw Bay, Lake Huron | 10 | 10 (100) | 2 (20) | 8.0 |
| Green Bay, Lake Michigan | 23 | 13 (56.5) | 3 (23.1) | 10.4 |

[a] Includes returning terns which were banded as chicks and as adults, percent region tenacity is given in parentheses
[b] Percent natal region tenacity is given in parentheses. Expected values were calculated considering that approximately 80% of marked terns were banded as chicks

### *Concentrations of PCBs and DDE in Plasma*

**PCBs:** PCBs were present in plasma of CTs at much greater concentrations than any other compound, including DDE, a persistent and ubiquitous metabolite of DDT. Concentrtions of PCBs have usually been the predominant chlorinated hydrocarbons in Great Lakes wildlife (Heinz *et al.* 1985; Struger and Weseloh 1985; Kubiak *et al.* 1989). Concentrations of PCBs were significantly different among nesting regions while concentrations in plasma of birds from different colonies within a region were similar. The colonies in Green Bay and Saginaw Bay exhibited the greatest concentrations, and the colonies in the Canadian portion of Lake Huron exhibited the least concentrations of PCBs. These findings are in agreement with other studies which have found greater concentrations of PCBs in Green Bay and Saginaw Bay than in other regions of the Great Lakes (Hoffman *et al.* 1987; Kubiak *et al.* 1989; Tillitt *et al.* 1991; Fox *et al.* 1991; Yamashita *et al.* in press). Caspian tern eggs from Pigeon Island, Lake Ontario, contained the greatest concentrations of PCBs of the seven colonies studied, but these concentrations were similar to those of CTs nesting on Gravelly Island, Green Bay during 1980–1981 (Struger and Weseloh 1985).

The greater concentrations of PCBs in CTs from Saginaw and Green Bays than in CTs from other nesting regions suggest that CTs from the former regions are exposed to greater concentrations of PCBs in their diet. The diet of CTs nesting in U.S. colonies consists mostly of alewives (57–65%, *Alosa pseudoharengus*), whereas CTs nesting in Canadian colonies have a more diverse diet and feed less on alewives (Ludwig

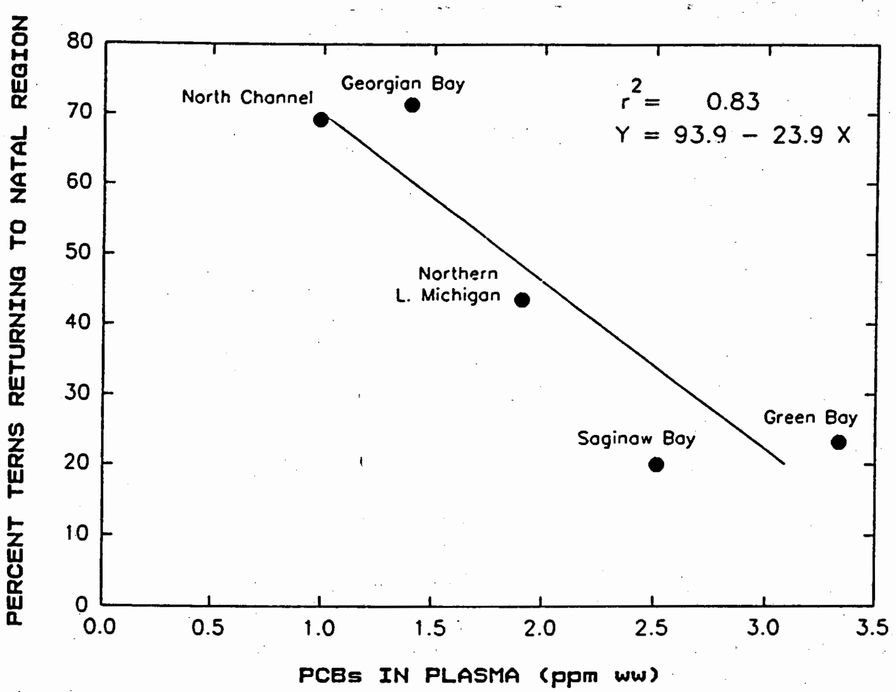


**Fig. 5.** Relationships between mean concentrations of PCBs in plasma and percent natal region tenacity. Table 5 gives the total number of individuals recovered from each region

1965; Shugart *et al.* 1978). This difference in diet may explain, in part, the difference in concentrations of PCBs in plasma, but it is likely that alewives from the Canadian area of Lake Huron contain lesser concentrations of PCBs than those from Saginaw and Green Bays.

**DDE:** The concentrations of DDE were less than those of PCBs and less than the threshold concentrations to cause significant eggshell thinning in CTs. Eggshell thinning is the main effect of DDE observed in birds during reproduction (Anderson and Hickey 1972). Concentrations of DDT/DDE have diminished considerably in the Great Lakes since the DDT ban in the United States in 1972 (Bierman and Swain 1982) and the small amounts detected in CTs are an indication of that reduction. The continuous detection of small amounts of DDT in plasma of fish-eating birds such as CTs, however, is also indicative that there may still remain sources of DDT/DDE, most likely atmospheric input, in the Great Lakes ecosystem.

The DDE : PCB ratios in plasma of CTs sampled in 1990 (Table 3) were similar to those observed in CT eggs at the Canadian Lake Huron, but were less than the DDE : PCB ratios observed in eggs at Lake Michigan colonies in 1980 (Struger and Weseloh 1985). This suggests that the sources of PCBs and DDE in the diet of CTs have remained proportionally constant at the Canadian Lake Huron until 1990, while a greater reduction of DDE sources relative to PCBs may have occurred at Lake Michigan during this period.

### *Associations and Similarities in Patterns of Chlorinated Hydrocarbons Among Caspian Tern Colonies*

As was the case for the North Channel and Green Bay colonies, the most similar patterns of contaminants were for those colonies that were most proximate. This similarity in contaminant patterns among colonies within the same region suggests that the distribution of CHs, particularly PCBs, is not uniform across the Great Lakes, but rather is concentrated around a few regions. Thus, CTs may be good indicators of regional levels of contamination by PCBs. Our former assumption considered that alewives, which are the main food of CTs, are also the main source of contaminants and feed within the same region where the CT colonies are. This may be the case, at least for Lake Michigan, where alewives move from deep waters to shallow, nearshore areas to spawn from late April to the end of August (Norden 1967) during the same period when CTs are nesting on nearshore islands in the Great Lakes.

### *Effects of Chlorinated Hydrocarbons on Productivity*

Productivity of Caspian terns at the Green Bay and Saginaw Bay colonies did not seem to be affected by the concentrations of PCBs observed in 1990. Concentrations of PCBs in plasma were 1.7–6 times less than those from pooled, live normal eggs (4.2–11 µg/g, wet wt) of CTs collected in 1988 from three Great Lakes regions (Yamashita *et al.* in press). Concentrations of PCBs as great or greater (18.5–39.3 µg/g, wet wt) than those observed in Saginaw Bay in 1988, however, did not seem to alter productivity of Great Lakes CTs during 1980–1981 (Struger and Weseloh 1985). This may indicate that CTs are less sensitive to the effects of PCBs than Forster's terns, which had reproductive failures in Green Bay during 1983 with median PCB levels in eggs of 22.2 µg/g (Kubiak *et al.* 1989).

Concentrations of DDE in plasma of CTs were relatively small, and not likely to cause any significant eggshell thinning. Eggshell thinning in Caspian tern eggs in the Great Lakes probably never reached a level (20%) that could have resulted in reproductive failures such as those observed in double-crested cormorants and herring gulls (Ludwig and Tomoff 1966; Weseloh *et al.* 1983; Struger and Weseloh 1985). Thus, populations of CTs in the Great Lakes have been less affected by DDE than those of other fish-eating birds.

The concentrations of dieldrin and trans-nonachlor in CTs plasma were even smaller than those of DDE and of no concern regarding negative effects on reproduction or mortality (Stickel *et al.* 1979; Mendenhall *et al.* 1983). Their frequency of detection, however, indicates that dieldrin and *trans*-nonachlor are still present in the Great Lakes ecosystem and monitoring for them should continue.

### *Relationships of Concentrations of PCBs and DDE with Age*

One of the original postulates of this study was that the continuous exposure of CTs to PCBs in their diet might result in accumulation of progressively greater concentrations of PCBs with increasing age. We assumed that concentrations of PCBs and DDE in plasma would be a good indicator of concentrations of these compounds in adipose tissue. The concentrations of PCBs and DDE in plasma did not increase with age, which suggests that the accumulation was seasonal rather than age-related. This seasonal acquisition likely occurs on their breeding grounds, although some accumulation could also occur on their wintering areas. Great Lakes Caspian terns winter from October to April as far south as the Caribbean, Colombia, and Venezuela (Ludwig 1965; L'Arrivee and Blokpoel 1988). Caspian terns may depurate PCBs during fall migration to areas where they are exposed to lesser concentrations of PCBs in their diet. Caspian terns arrive back in the Great Lakes colonies in late April and begin laying between 5 and 15 May. At the time of arrival, CTs probably contain lesser concentrations of PCBs than when they departed. We collected blood in early June at the end of their first laying period. By this time, CTs had been in their nesting areas for about a month, a period long enough for them to accumulate PCBs from fish in their diets, thus reflecting local concentration of PCBs rather than accumulation of PCBs with age or during migration. A similar pattern likely explains the accumulation of DDE in CTs during the breeding season since PCBs and DDE were strongly correlated.

The accumulation of PCBs in CTs at the nesting colony must be rapid since the birds begin to put on fat for the nesting and incubation period. Increases in concentrations of compounds such as PCBs with time spent on the Great Lakes has been observed in common terns (Gilbertson1974) and in CTs from first to second clutches in Saginaw Bay (Yamashita *et al.* in press). During the early stages in laying, the accumulation of PCBs in adipose tissue may still be increasing due to continuous uptake. As intake of PCBs continues, greater concentrations in fat would contribute to greater deposition of PCBs in eggs.

### *Relationships Between Concentrations of Chlorinated Hydrocarbons in Plasma and in Other Compartments*

It has been suggested that concentrations of CHs in plasma may not reflect concentrations in adipose tissue (Monro 1990; Schecter *et al.* 1991), particularly in situations of continuous daily intake. Consequently, analysis of adipose tissue where lipophilic substances bioaccumulate may provide a more significant correlation of the accumulation of PCBs with age. Henny and Meeker (1981) found a significant correlation between concentrations of DDE in the diet and those in the blood of American kestrels (*Falco sparverius*). Furthermore, significant relationships between DDE in plasma and DDE in body lipids have been observed in field and laboratory experiments with raptors (Henny and Meeker 1981), mallards (Friend *et al.* 1979) and white-faced ibises (Capen and Leiker 1979). Therefore, it is likely that concentrations of PCBs and DDE in blood of CTs were significantly correlated with those in adipose tissue. The total mass of DDE in bodies of white-faced ibises oscillated according to their storage cycle and lipid mobilization. Thus, since CTs spend over half of their annual cycle outside the Great Lakes, a considerable amount of PCBs are probably eliminated when storage fats are utilized during migration.

### *Relationships Between Concentrations of PCBs in Plasma and Colony Site Tenacity*

Analysis of the locations where CTs were recaptured for blood collection indicated that colony site tenacity was strong (greater than 80%), except at colonies in Green Bay where it was just above 50% (Table 5). When L'Arrivee and Blokpoel (1988) compared site fidelity and intercolony movement of Great Lakes CTs based on the analysis of 1,126 recoveries, they observed that 70% of adults returned to the same lake and that there was a strong tendency (60–70%) for CTs (especially first year breeders) to return to a different colony from where they were born. Our analysis of band recoveries was based on regions assuming that region fidelity is more likely to occur than colony fidelity due to shifting colony sites within a region. This is particularly true since birds have been shown to move from one colony to another even during the course of one nesting season (Cuthbert 1985). In our case, region fidelity was great except at Green Bay where only about half of the adult CTs returned to the same area to breed. This is in agreement with the analysis of 1,126 band recoveries which indicated that the number of CTs which returned to breed at Green Bay was significantly less than expected ($P < 0.001$); whereas the number of adult CTs returning to other U.S. colonies was not different from expected and was greater than expected at the Canadian colonies (L'Arrivee and Blokpoel 1988; Ludwig unpublished). The reasons for this are unknown. Caspian terns are less likely to return to their regular breeding area (natal region) if they experienced reproductive failures the previous year (Cuthbert 1988). Reproductive failures in CTs could be attributed to storm events, predation, human disturbance (Cuthbert 1988; Shugart *et al.* 1978), or to effects of planar halogenated hydrocarbons such as PCBs, PCDDs, and PCDFs (Hoffman *et al.* 1987; Kubiak *et al.* 1989). Whether PCBs or other halogenated hydrocarbons have any influence on colony site fidelity is not known.

The possible influence of PCBs on colony site tenacity is clearer when natal site rather than regional fidelity is considered. When the proportion of adults which had been banded as chicks in their natal area (Table 5) was correlated with mean PCB concentrations for each region, a statistically significant negative correlation was observed between mean concentrations of PCBs by region and natal fidelity (Figure 5). However, the sample size is small and more data on banding returns will be needed to further assess this phenomenon.

Support for the relationship of reduced natal site fidelity at the colonies most contaminated with PCBs, possibly due to increased mortality of young, can be obtained from observations of poor reproductive success due to increased concentrations of PCBs and other PHHs in fish-eating birds from Green Bay and Saginaw Bay (Hoffman *et al.* 1987; Kubiak *et al.* 1989; Tillitt *et al.* 1991). Additional support is provided by the fact that 62% of the bands recovered up to 1963 from chicks tagged from 1922 to 1953 corresponded to fledged CTs that died before the first year of breeding (Ludwig 1965). One could postulate that PCBs accumulate in postfledging individuals in a manner similar to what has been observed in herring gulls (Anderson and Hickey 1976) to concentrations which could cause increased mortality during migration due to utilization of fat reserves. It is also possible that post-fledging terns (juveniles, immatures, and subadults) have greater susceptibility to PCBs and other PHHs, which may result in greater mortality (see Ludwig 1979; Ludwig *et al.* in press). If postfledging mortality is greater than that of adults, then the number of returning first or second year breeders might be expected to be less in Green Bay and Saginaw Bay than in other regions. Hatching success and number of young fledged/nest for CTs were basically the same for all nesting colonies during 1990, although reproductive failures have been observed in other years (Kurita *et al.* 1987). It is also possible that mortality of chicks after they leave the nest, but before they are fully fledged, is greater at colonies where concentrations of PCBs are greater, due perhaps to increased predation or diminished food provisioning by their parents. Due to the difficulty of identifying unmarked chicks, it was impossible to account for the fate of chicks wandering out of their nests.

Dispersal of first- and second-year breeding CTs may be another factor which contributes to reduced natal region tenacity in regions with greater concentrations of PCBs. It has been observed that CTs that fail during the first breeding attempt usually desert that colony for a nearby colony, whereas CTs that fledge at least one young the former season return to breed to the same colony the following year (Cuthbert 1988). It is also known that most CTs recruiting into new colonies are first time breeders, perhaps due to difficulties in establishing territories at their natal colonies (Gill and Mewaldt 1983; L'Arrivee and Blokpoel 1988). Breeding inexperience and lack of available nesting sites may explain perhaps some of the dispersal which was observed from the Canadian portion of Lake Huron colonies where concentrations of PCBs were the least. However, significantly less natal fidelity at Saginaw and Green Bay colonies than at the Canadian Lake Huron colonies may be exacerbated by greater concentrations of PCBs, which may result in poorer reproductive success, increased pre-adult mortality, or altered reproductive behavior as has been observed in Foster's terns from Green Bay (Hoffman *et al.* 1987; Kubiak *et al.* 1989). For the two regions with the greatest concentrations of PCBs, Green Bay chicks apparently were able to disperse more than Saginaw Bay chicks. Of 23 CTs banded as chicks in Green Bay, 10 were recaptured elsewhere (five at the Beaver Islands, two at the North Channel, and three at the Saginaw Bay CDF), whereas all (10) recaptures of terns banded at the CDF were from the CDF. The Caspian tern colony at the Saginaw Bay CDF was established in 1982, thus there may not yet be many banded individuals to assess their dispersal to other colonies.

In summary, the main factors contributing to the lower return (23%) of CTs to their natal colony in Green Bay may be greater dispersal exacerbated by early reproductive failures, and greater mortality of fledglings and young before reaching breeding age, which are known to be affected by exposure to PCBs. A similar situation could be occurring in Saginaw Bay, although no recoveries at other sites were obtained during our limited sampling. The Saginaw Bay colony is relatively new and more time will be needed to determine the dispersal pattern of the banded young produced at this site. Moreover, CTs at the Saginaw Bay CDF have exhibited lesser and more variable egg viability, wasting syndromes in chicks, and lesser fledging rates for the last four years (Ludwig *et al.* in press).

## Conclusions

The concentrations of PCBs in plasma of CTs were between two and six times less than those observed in live normal eggs from the same colonies in 1988 (Yamashita *et al.* in press). These concentrations of PCBs are of concern because of their association with abnormalities described as GLEMEDS syndrome in Great Lakes fish-eating birds (Gilbertson *et al.* 1991). Productivity, however, was good during 1990 and populations of CTs have remained basically stable for the last six years (Ludwig unpublished). More studies are needed to test the hypothesis that PCBs may be directly linked with reduced survivorship of CTs from fledging to breeding age in more contaminated areas. Total concentrations of PCBs may not provide the best correlation with the degree of reproductive impairment, anomalies, and deformities observed in Great Lakes fish-eating birds; however, coplanar PCBs and other PHHs have been directly linked to these anomalies. A statistically significant correlation was observed between concentrations of total PCBs and concentrations of three coplanar PCBs with the greatest potency to cause toxicity in mammals (Tanabe *et al.* 1987) and between total PCBs and TCDD-equivalents in chinook salmon (*Oncorhynchus tshawytscha*) fillets from Lake Michigan (Williams *et al.* 1992). Thus, total concentrations of PCBs are reliable indicators of greater concentrations of coplanar PCBs and TCDD-EQ, both of which have been associated with reproductive impairment in fish-eating birds. The results suggest that CTs which feed or nest in areas near Saginaw Bay and Green Bay are more likely to be affected by greater concentrations of PCBs than CTs nesting in other areas of the upper Great Lakes.

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