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The biological pathway and effect of PCBs on common terns in Lake Michigan

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Abstract Poly-chlorinated biphenyls (PCBs) have been recognized as a significant contaminant in the Great Lakes ecosystem. Although PCBs are implicated in the reduced survival and reproductive success of several piscivorous bird species, the biological pathway in which PCBs bio-accumulate remains largely unknown. This study investigates the two most likely biological pathways, suggested via research on Great Lakes sport fish, by which PCBs would be acquired by common terns (Sterna hirundo), a piscivorous species of conservation concern. The first proposed pathway is through atmospheric deposition of PCBs which are subsequently acquired by filter-feeding fish (e.g., alewives, Alosa pseudoharengus). An alternative pathway is via the biodeposits of zebra mussels which are consumed by shallow water fish (e.g., round gobies, Neogobius melanostomus). Because common terns breed in near-shore sites where concentrations of zebra mussels are found, as well as forage in more pelagic environments it is possible that either or both pathways may be contributing to their PCB exposure. Field experiments and stable isotope analyses suggest the most likely pathway by which terns are exposed to PCBs is via alewives, similar to how apex predators such as lake trout acquire PCBs. Biodeposits from zebra mussels do not appear to be a significant factor in PCB accumulation in terns. We quantified extremely poor parental attentiveness during incubation. Although we cannot determine whether poor parental attentiveness alone or in combination with PCB contamination led to low hatching success, accumulation of PCBs appears to have significant impacts on the overall reproductive success of common terns.

Keywords Alewives · Biological pathway · Common terns · Parental attentiveness · PCBs

Introduction

The bioaccumulation of polychlorinated biphenyls (PCBs) can have significant affects on adult birds, eggs, and nestlings (Fox et al. 1991; Ludwig et al. 1996). The effect of PCBs on birds is variable, but can include direct mortality, physical deformities, reduced hatching success, and aberrant behaviors (Custer et al. 1983; Ohlendorf et al. 1985; Becker et al. 1993; Yamashita et al. 1993; Bosveld et al. 1995; Lorenzen et al. 1997; Stapleton et al. 2001a). Piscivorous birds appear to be particularly susceptible to the bioaccumulation of PCBs (Grasman et al. 1998; Kunisue and Tanabe 2008). However, the biological pathways by which PCBs are accumulated by the birds are largely unknown. Many piscivorous birds that potentially could be impacted by environmental contaminants are found in the Great Lakes ecosystem. Although little is known about bird food webs in the Great Lakes, a large volume of research has been...
conducted on the biological pathways by which PCBs are accumulated in sport fish (e.g., Stapleton et al. 2001b; Streets et al. 2006; Ng et al. 2008; Helm et al. 2008). These and other studies within the Great Lakes ecosystem have generally elucidated two pathways. The first involves the resuspension of contaminants in the sediment and/or atmospheric deposition of PCBs into the water column and assimilation by predatory fish through the food chain (Stapleton et al. 2001b). Once associated with seston and detritus within the water column, PCBs are transferred to small pelagic fish such as alewives (Alosa pseudoharengus), and then onto the apex pelagic predators such as lake trout (Salvelinus namaychus) and Chinook salmon (Oncorhynchus tshawytscha; Kiriluk et al. 1995; Stapleton et al. 2001b). An alternate biological pathway was established following the introduction of two exotic species. The introduction of zebra mussels (Dreissena polymorpha) and round gobies (Neogobius melanostomus) into the Great Lakes basin has been found to facilitate the bioaccumulation of PCBs in piscivorous fish (Bruner et al. 1994; Cho et al. 2004; Kwon et al. 2006). Zebra mussels filter PCBs from the water column and sequester them in both their soft tissues and shells. However, mussels also deposit a significant proportion of the PCBs in their feces and pseudofeces (Cho et al. 2004; Kwon et al. 2006). These biodeposits can then be ingested by round gobies, which in turn are preyed upon by piscivorous fish, most often small-mouthed bass (Micropterus dolomieu).

For many fish species the pathway most likely to contribute to the bioaccumulation of PCBs can be elucidated by their primary forage items. Pelagic species, such as lake trout, acquire PCBs from filter feeding fish, while species that prefer shallow water with underwater structure (e.g., small-mouthed bass) bioaccumulate PCBs via fish that forage on or near the biodeposits of zebra mussels (Hubert and Lackey 1980; Kwon et al. 2006). Zebra mussels are unlikely to be important to many pelagic species because they occur primarily in shallow areas with underwater structure. Many piscivorous birds such as the common tern (Sterna hirundo) breed on islands or peninsulas along the Great Lakes. They forage not only in nearby shallow water where underwater structures support large colonies of zebra mussels, but also in open water where pelagic fish (e.g., alewives) are sought. Therefore, they may be exposed to PCBs by either or both pathways.

Although the mean concentration of PCBs in the Great Lakes fisheries stock continues to decline (Jackson et al. 1998; Lamon et al. 2000), atmospheric deposition and resuspension of PCB laden sediments pose a continuing health hazard to both wildlife and humans (Baker et al. 1991; Turyk et al. 2006). Indeed, the bioaccumulation of PCBs in Great Lakes sport fish poses a human health concern for those consuming fish (Turyk et al. 2006), as well as a conservation concern for piscivorous birds given the population declines of many of these species (e.g., common terns). Therefore, it is imperative to understand both the biological pathway of PCBs to the terns and to identify the potential impacts of PCB consumption on piscivorous birds of conservation concern, and in particular, the impacts of exposure on their reproductive success.

Researchers have documented wide variations in how PCBs affect the physiology and behavior of different bird species. A number of studies have measured PCBs in common tern tissues, and have documented reduced hatching success, abnormal embryos, and congenital deformities due to elevated PCB levels (Hays and Risebrough 1972; Gilbertson et al. 1976; Gilbertson et al. 1993; Becker et al. 1993; French et al. 2001). PCB exposure in adult birds has also been shown to cause endocrine disruption, which in turn may lead to reduced parental attentiveness and lower hatching success (Kubiak et al. 1989; Bustnes et al. 2001; Stapleton et al. 2001a; Fisher et al. 2001). Although there has been a trend toward reduced PCB concentrations and fewer observations of gross deformities in Great Lake piscivorous birds over the last decade, there remains the potential for significant consequences of PCB consumption on bird populations.

Poor parental attentiveness can be particularly detrimental for species such as terns and gulls that nest in exposed areas of sand or rock. Studies of Forster’s terns (Sterna forsteri) have found that eggs left unattended in the sun can reach 50.0°C within 25 min (Grant 1982). Generally, once a bird egg reaches 40.5°C some embryonic damage occurs (Dawson 1984). Olsen (1989) found that eggs exposed to high temperatures shortly after being laid can result in embryonic deformities. Under some condition, even short periods of high temperatures can also be fatal; the upper lethal internal egg temperature varies between 43.0 and 49.0°C (Barrett 1980; Bergstrom 1989). Although nest temperatures are not a direct measure of egg temperature, Bergstrom (1989) estimated that when nest temperatures reached 43.2°C, internal egg temperatures are 42.0°C. At the other extreme, embryos in eggs that dropped below 26.0°C simply stop developing (Webb 1987). Research on parental attentiveness in common terns has shown that if adults are frequently flushed while incubating at night when temperatures are cool, the temperature of the eggs can drop (Arnold et al. 2006), extending the amount of time required for the egg to hatch (Wendeln and Becker 1999).

This study was designed to determine whether common terns were being exposed to ecological contaminants (primarily PCBs) at a colony in the southern portion of Lake Michigan. Field experiments were conducted to identify the biological pathways to PCB exposure and accumulation in terns; the suspected pathway was then further investigated using stable isotopes of carbon and nitrogen. Finally, parental attentiveness of common terns was quantified to...
determine if PCB contamination may be indirectly affect
common tern hatching success, implicating environmental
contamination as a limiting factor for this species.

Methods

Study species and study location

The common tern is as an endangered species in Illinois
(Nyboer et al. 2006) and a species of federal concern (U.S.
Fish and Wildlife Service 2002). In Illinois, the sole
remaining nesting colony is located at the Naval Station
Great Lakes (NSGL), in northeastern Lake County (Fig. 1).
The colony is located within an artificially created harbor, a
site with extensive underwater structures, including
breakwaters and docks, which support large concentrations
of zebra mussels. The site located only 5.8 km down-cur-
rent of Waukegan Harbor, a United States Environmental
Protection Agency Area of Concern due to environ-
mental contamination (http://www.epa.gov/greatlakes/aoc/
waukegan.html). Despite intensive management efforts to
exclude mammalian nest predators from the tern colony the
survival of fledgling terns is low and renesting is common
(Jablonski et al. 2005). Observations of deformities in
hatchlings (i.e., compromised feather development and
cross-bill), lethargic behavior of young birds, and lesions
(Jablonski et al. 2005) suggests the influence of environ-
mental contaminants. Common terns forage on a wide
variety of items but their primary food source is small fish
(<150 mm), upon which they generally feed in relation to
their availability (Moore and Morris 2005). Although no
data have been systematically collected on which species
common terns preferentially forage on at NSGL, spottail
shiners (Notropis hudsonius), alewives, and other small fish
have been observed being brought to the colony to feed
young (Jablonski et al. 2005).

Tern exposure to environmental contaminants

The endangered status of common terns limited active col-
lection of live material for this study (i.e., chicks and eggs).
Therefore, most samples were fortuitously collected to
assess environmental contamination: we did remove the first
egg laid in 10 nests. In order to identify the first egg laid in a
nest, the colony was visited daily and eggs within known
nests (i.e., all nests were marked with a 0.3 m wooden
stake), were marked with pencil. To ensure that egg col-
clection did not induce abandonment, the first egg was not
collected until after the second egg was laid. These “fresh”
eggs (n = 10) were all removed in late May. “Failed” eggs
(n = 8) were collected in late June and early July after
individual nests were confirmed abandoned. Failed eggs
were categorized as pipping (n = 3), intact (n = 2), or
cracked (n = 3). Small (1–2 days after hatching) and large
(>20 days, collected following a severe storm) morbid
nestlings and one adult tern were analyzed; samples were

Carbon Dynamics, Inc., an independent laboratory
located in Springfield, Illinois, analyzed all samples used in
this study. The presence and amount of PCBs was deter-
mined using the US EPA’s CDI SOP TA-TN-1656
(Revision A) protocol. Individual samples were homoge-
nized with a mechanical blender, dried with sodium sulfate,
and then extracted with a methylene chloride: hexane
solution (1:1) in a Soxhlet extractor. The organic extract
was concentrated to approximately 5 ml and subjected to
GPC cleanup. The extract was re-constituted to 1 ml of
hexane and analyzed by gas chromatography mass spec-
trometry with a negative chemical ionization source
(GC/MS/NCI). The detection limits for PCBs were
0.10 µg/kg for Aroclor 1016,1221,1232,1242,1248,1254,1260
and congeners #s 77, 114, 168,180, 0.20 µg/kg for congenger
#s 79,118,122,123,126,157,167, and 0.50 µg/kg for congenger
156. The total PCB concentration level was the sum of the
PCB congenger concentrations and were presented as wet
weights. For the calculation of total PCBs, individuals PCB
congeners below the detection limit were given a value of zero.

Because heavy metals have been shown to affect the
reproductive success and cause deformities in piscivorous
birds (Hays and Risebrough 1972; Burger and Gochfeld
1997; Lam et al. 2005) initial samples were analyzed for
selenium, mercury, lead, and cadmium in accordance with
CDI SOP TA_TN-IMQ Revision 0. A pre-measure volume
of approximately one gram of tissue was acid digested with

![Fig. 1 Location of the common tern colony at the Naval Station
Great Lakes in Lake County, Illinois](image_url)
NHO₃ and H₂O₂ in accordance with the appropriate sample preparation methods described in EAP OSW Methods 3050B and 6020 prior to filtration. Interference check and quality control solutions were also prepared. Multi-elemental determination of analytes was achieved by measuring of ions produced by radio-frequency inductively coupled plasma where analyte species are nebulized and the resultant aerosol was transported by argon gas into the plasma torch. Ions produced in the plasma were sorted according to their mass-to-charge ratio and quantified with a channel electron multiplier. Appropriate internal standards were used in the analysis as outlined in EPA protocols. Qualitative identification of the parameter in the extract was performed using the most abundant isotopic characteristic mass (m/z). Quantitative analyses were performed using internal standard techniques with a single characteristic m/z. The detection limit for selenium was 0.200 mg/kg, cadmium 0.012 mg/kg, mercury 0.050 mg/kg, and lead 0.002 mg/kg, all heavy metal data were calculated as wet weights.

Biological pathway

Two field experiments were conducted to investigate the potential biological pathways of PCBs to terns. First, we constructed eight PVC cylinders (1.3 m long by 20 cm in diameter) that housed an inner metal mesh cylinder. Four cylinders housed zebra mussels collected from within the harbor, while the other four served as controls and contained gravel that approximated the size of mussels used in the study. The gravel cylinders were used to replicate the flow of water through the cylinders containing zebra mussels. Small slits were cut vertically along each PVC cylinder to allow water circulation and a glass collection jar was attached at the bottom of each cylinder. The collection jars were emptied every 2 weeks. The cylinders were suspended in the water column in approximately 3 m of water. The concentrations of PCBs in material collected from the jars were compared between cylinders containing mussels (treatment) and those containing gravel (control). The intent was to evaluate mussel biodeposits, seston, detritus and other organic material gathered from the water column. If zebra mussels were facilitating the exposure of PCBs to forage fish sought by common terns. If zebra mussels were facilitating the exposure to PCB contaminants, the fish in treatment cages ultimately would have higher levels of contaminants than the fish inside control cages.

Stable isotope analysis

Carbon (i.e., ¹³C:¹²C) and nitrogen isotope ratios (i.e., ¹⁵N:¹⁴N) were used to analyze source links within the local food web. Samples of zebra mussel tissue, macroinvertebrates, phytoplankton, leaf litter, forage fish, and morbid tern young were used in the isotope analyses to establish the food pathway from prey base to the common terns. All sample types were placed in a desiccator, dried at 55°C for 48 h and then ground with mortar and pestle. Samples were then packed into individual tin capsules and sent to the University of California at Davis Stable Isotope Lab for C and N isotope analysis. The mixing model Isosource® (Phillips and Gregg 2001) was used to determine which potential food sources were most likely to explain the carbon and nitrogen isotope ratios of the fish: all possible combinations of each source contribution (0–100%) were examined in 1% increments. Stable isotope ratios were expressed in δ notation as parts per thousand according to the following:

\[
δX = \left[ \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} \right) - 1 \right] \times 1000,
\]

where X = ¹⁵N or ¹³C, R = ratio, ¹⁵N/¹⁴N or ¹³C/¹²C. Rstandard for ¹⁵N is atmospheric nitrogen, and for ¹³C it is Pee Dee belemnite. Samples were also analyzed for total carbon and nitrogen.

To normalize potential food items for trophic enrichment, a value of +0.5 was used for δ¹³C (France, 1996), and +3.4 was used for δ¹⁵N (Minagawa and Wada 1984). Combinations that summed to the observed mixture isotopic signatures with ±0.1% were considered feasible solutions. Percentages

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of source contributions to diet were presented as medians, 1st and 99th percentiles of all iterations for alewives.

Parental attentiveness

Incubation patterns in nesting terns were investigated using temperature sensors (thermochrons) placed directly beneath eggs in each active nest. Individually numbered nests were monitored daily in during the laying stage and every 2–3 days during incubation to determine the number of eggs that hatched and the survival of nestlings. Temperature sensors recorded the nest temperatures every 15 min throughout the duration of nesting activity. Common terns in the NSGL colony consistently laid three egg clutches (Jablonski et al. 2005). Thermochrons (i-buttons), temperature sensors used for this study were developed by Dallas/Maxim (Sunnyvale, California) and used an embedded computer chip with an integrated 1-wire transmitter/receiver, thermometer, clock/calendar, and thermal history log. Individual nest temperature data from each thermochron were analyzed to determine when temperatures exceeded temperatures known to damage developing embryos. Minimum and maximum temperatures were documented for each nest during incubation. These data were compared with the number of live chicks that hatched from each monitored nest for the 2006 and 2007 breeding seasons. We were not able to collect adults in order to compare potential PCB loads of the eggs or parents with parental attentiveness.

Statistical analyses

T-tests were used to compare contaminant concentrations between tern chicks of different age classes, contaminant loads between biodeposits and seston/detritus collected from below suspended PVC cylinders, contaminants in the sediments and fish before and after enclosures were established, and between contaminant concentrations in shiners, gobies, and amphipods (Diporeia spp) in treatment and control enclosures at the conclusion of that experiment. T-tests also were also used to compare the number of eggs that hatched from nests that recorded temperatures exceeding 40.5°C and those that did not. Standard errors were reported unless otherwise stated.

Results

Tern exposure to environmental contaminants

Common terns at NSGL were found to have low tissue concentrations of selenium (n = 36, 1.30 mg/kg) and a near absence of cadmium (n = 3, <0.02 mg/kg), mercury (n = 3, <0.18 mg/kg), and lead (n = 3, <0.36 mg/kg). In contrast, high concentrations of PCBs were prevalent, and as chicks aged from newly hatched (<2 days old) to near fledging (14–20 days old) average total PCB loads increased from 3,009.50 ± 1185.08 µg/kg to 4,955.51 ± 1400.19 µg/kg (t = 7.93, df = 11, P = 0.016; Table 1). Over 95% of the total PCB concentrations were due to Aroclor 1254.

Biological pathway

PCBs were detected in all field experiments within the NSGL harbor. In the trials involving suspended PVC tubes, there were higher concentrations of PCBs in the collection jars beneath control cores (i.e., with gravel: 50.21 ± 6.05 µg/kg) than those beneath treatment tubes containing mussel biodeposits (27.15 ± 7.93 µg/kg; t = 6.05, df = 6, P = 0.03; Fig. 2).

For the experimental fish enclosure studies, analyses of sediment samples from below the cages showed no significant difference in PCB concentrations before and after the experiment in either the control cages (t = 0.33, df = 13, P = 0.38) or the treatment cages (t = 0.71,

![Fig. 2](image)

**Fig. 2** Total PCB concentrations (µg/kg) in the collection jars positioned below suspended mussel colonies and those below controls represented by gravel. Values illustrated are means with standard errors.
df = 13, \( P = 0.25 \); Fig. 3). Similarly, we found no statistical difference in selenium concentrations in both the sediment samples before and after the experiment (0.26 \( \pm \) 0.18 mg/kg vs. 0.33 \( \pm \) 0.33 mg/kg; \( t = 0.17, \) df = 11, \( P = 0.44 \)). No alewives survived the 169 days of confinement and no remains were available for testing. Although none of the alewives survived, it should be noted that the stock alewives had higher concentrations of PCBs (955.77 \( \pm \) 368.11 \( \mu \)g/kg) than stock shiners (102.80 \( \pm \) 29.48 \( \mu \)g/kg; \( t = 2.31, \) df = 4, \( P = 0.04 \)). There was no difference in PCB accumulation in shiners, neither the shiners in the control nor treatment enclosures had higher concentration than the stock shiners (\( t \geq 1.08, \) df = 5, \( P > 0.17 \); Fig. 3). Likewise, we did not detect any differences in selenium concentrations between control and treatment cages following the trial period (0.25 \( \pm \) 0.25 mg/kg vs. 0.30 \( \pm \) 0.20 mg/kg; \( t = 0.29, \) df = 3, \( P = 0.39 \)). Round gobies had higher concentrations (10\( \times \)) of PCBs in the treatment cages (468.09 \( \pm \) 97.19 \( \mu \)g/kg) as opposed to the control cages (45.78 \( \pm \) 37.95 \( \mu \)g/kg; \( t = 9.76, \) df = 2, \( P = 0.01 \); Fig. 3).

Stable isotope analysis

Using a stepwise enrichment value of 3.4 for \( \delta^{15} \)N and 0.5 for \( \delta^{13} \)C, it appeared that alewives were the primary local food source for common terns (Fig. 4). The mixing model Isosource\(^\circ\) was then used to determine the alewife food sources. Table 2 lists the possible combinations ranging from the 1st to the 99th percentile. Based on the results, alewives appeared to have feed primarily on amphipods and rarely on the biodeposits of zebra mussels. The ratio of \( \delta^{15} \)N to \( \delta^{13} \)C illustrates that common terns were the apex predator of the food chain we evaluated (Fig. 4).

Parental attentiveness

The temperature sensors placed in active tern nests suggest very poor attentiveness (\( n = 20 \) nests; Fig. 5). Assuming that temperatures above 40.5°C impaired embryonic development, we compared the number of eggs that
Table 2 The mixing model Isosource® was used to determine food sources for alewives

<table>
<thead>
<tr>
<th>Food source</th>
<th>Median (%)</th>
<th>1st percentile (%)</th>
<th>99th percentile (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodeposits</td>
<td>0.5</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Amphipods</td>
<td>69</td>
<td>68</td>
<td>72</td>
</tr>
<tr>
<td>Leaf litter</td>
<td>29.5</td>
<td>28</td>
<td>72</td>
</tr>
<tr>
<td>Algae</td>
<td>0.5</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

Represented is the possible diet composition for alewives; combinations ranging from the 1st to the 99th percentile. Based on the calculated distribution, alewives appear to feed primarily on amphipods and rarely on the biodeposits of zebra mussels.

Fig. 5 Median nest temperature recorded via temperature sensors in common tern nests. Temperatures were recorded every 15 min throughout the course of the incubation period. The line at 40.5°C represents the temperature at which embryonic egg development has been shown to be deleteriously influenced. The solid bars at the bottom of the graph are the number of tern chicks that successfully hatched from each nest (all nests had three-egg clutches).

hatched between nests that did and those that did not have temperatures reach ≥40.5°C. The number of eggs that hatched in a nest that had temperatures above 40.5°C (0.77 ± 0.28) was lower than those in nests that never reached 40.5°C (1.90 ± 0.39; t = 2.35, df = 17, P = 0.02).

Discussion

Common tern eggs and nestlings at the NSGL in southern Lake Michigan were found to be contaminated with high levels of PCBs, while there were very low concentrations of selenium, mercury, and lead. Isotope analyses suggest alewives are the primary prey of common terns, which is consistent with observations of fish being brought to nestlings in the colony. Thus, the pathway of environmental PCBs from Lake Michigan waters to terns appears to be similar to the pathway described for pelagic fish such as lake trout that accumulate PCBs via alewives. Stapleton et al. (2001b) quantified the PCB load of lake trout in Lake Michigan at approximately 1200 µg/kg, and Streets et al. (2006) found similar PCB levels in their sampling efforts of Lake Michigan lake trout (1,600–1,900 µg/kg). Although only one adult tern was analyzed in this study and comparisons between taxa are difficult due to differences in physiology and lipid-content, among other factors, it appears that common terns may have an even greater PCB load than lake trout (2,530.47 mg/kg, n = 1).

The lower PCB concentrations collected from beneath suspended cylinders containing zebra mussels as compared to those cylinders containing gravel, suggested that zebra mussels were sequestering PCBs from the water column and retaining them in their shells or tissue. It also appears that seston and other detritus in the water column are contaminated with PCBs. Although adult alewives are phytoplankton feeders, young alewives regularly feed on amphipods likely Diporeia spp. (Mills et al. 1992; O’Gorman et al. 2000; Pothaven and Vanderploeg 2004; Hondorp et al. 2005; Stewart et al. 2009). The amphipods sampled from the harbor had relatively high PCB concentrations (Fig. 3), and the PCB concentrations were similar in amphipods whether from enclosures with or without zebra mussels.

Our isotope analyses suggested that zebra mussel biodeposits were at most a very small component of the food chain of common terns. This finding was supported by both the fish enclosure study and the natural history of the fish species most closely associated with the mussel biodeposits (round gobies). In the fish enclosure experiment, gobies exhibited the greatest differences in PCB levels between those enclosures with and without zebra mussels. This was not surprising considering that studies have shown that gobies readily ingest mussel biodeposits and bioaccumulate PCBs from these biodeposits (Cho et al. 2004; Kwon et al. 2006). Given that common terns are aerial, plunge foragers and gobies are known to forage at or near the lake bottom, it was unlikely that gobies would constitute a significant portion of their diet. Although the tern colony may be within a few meters of large zebra mussel colonies, terns likely are not exposed to this PCB source due to their preference for fish near the water’s surface. The most likely pathway of PCBs to terns is via seston, amphipods, and alewives. Unfortunately, no alewives survived the enclosure experiment so it was impossible to definitively examine this link in the food web. While terns were observed catching alewives in shallow waters and in close proximity to zebra mussel colonies, it does not appear that mussel biodeposits were a significant part of the alewife food chain.

There has been a general decline in PCB concentrations in the Great Lakes (Lamon et al. 2000). However, the most common PCB in this study was Aroclor 1254, a chemical that was used in electrical equipment prior to 1950 (Fiedler 1997). Over a half century later Aroclor 1254 appears to be...
a leading factor in reduced reproductive success of common terns in Lake Michigan. Impaired reproduction was due to both poor parental attentiveness (i.e., reduced hatching success) and direct mortality of young. Although we did not capture and inspect all nestlings, several individuals were documented with lesions and developmental deformities and numerous nestlings died within a day of hatching (Jablonski et al. 2005). It should be noted that our sample of tern nestlings did not represent a random sample of nestlings because we only analyzed only those nestlings that were found dead. If nestlings with higher PCB concentrations were more likely to die it would skew our average PCB loads higher. However, ten of the 18 eggs we analyzed were “fresh” eggs in a clutch and randomly selected. The PCB loads we detected in those samples were much higher than those found in other similar studies where PCBs impacted reproductive success. For example, a study in Germany documented hatching failure in common tern eggs with an average PCB load of 5,451 µg/kg (Becker et al. 1993). The average concentration of PCBs in eggs that failed to hatch in our study was 13,269 µg/kg in 2007, well above that measured by Becker and his colleagues. Although only one adult was analyzed for PCBs (2,530.47 µg/kg), the high levels of PCBs in eggs suggested elevated levels in the parents as well.

PCBs may be impacting the tern population both through direct physiological damage to embryos but also via poor parental attentiveness. High concentrations of PCBs in adult terns may lead to endocrine disruption and preternatural parental behavior which may in turn lead to failed eggs. High levels of PCBs have been documented to affect parental/nest attentiveness in birds that nest in similar habitat similar to terns (glaucous gulls, Larus hyperboreus; Bustnes 2001). The preferred nesting habitat of open sand made nests highly susceptible to over-heating. We recorded temperatures of >55°C in two nests, and only one egg hatched from those nests. Also some of the deformities we observed in nestlings may be the result of high egg temperatures which can lead to embryonic deformities (Olsen 1989). We were unable to correlate deformities with nest temperatures because several deformities such as not growing primary feathers was not noticed until the young birds were very mobile and the individuals could not be assigned to a nest. It also should be noted that nest temperatures could have been greater than the actual temperature of the embryo in the egg. Poor nest attentiveness has been shown to result in prolonged incubation periods (Kubiak et al. 1989; Wendeln and Becker 1999; Fisher et al. 2006), which we noticed on several occasions when monitored nests exceeded the anticipated 22–23 day incubation period.

Although most of the sampling occurred in 2007, a few young and eggs were collected in 2005 and 2006 for analysis. PCB concentrations in young and eggs differed significantly between 2005 (682.79 ± 353.70 µg/kg) and 2006, 2007 (9,134.67 ± 1,458.52 µg/kg; t = 5.61, df = 35, P < 0.01). Although those differences could have been due to our smaller sample size in 2005 (N = 4 vs. 33), there also may be large variation in contaminant levels between years. In years with a higher abundance of alewives, herring gulls (L. argentatus) were found to have higher concentrations of PCBs (Herbert et al. 1997). It is possible that a reduced alewife population in 2005 may have accounted for lower PCB concentrations. Behavioral observations suggested that the second most common prey after alewives were spottail shiners and our isotope analysis supported this contention. A comparison of the stock fish used in the enclosure study suggested that on average alewives had higher PCB loads than shiners. Therefore, a reduction in alewives may have reduced the terns’ exposure to PCBs. Selective feeding to the young terns of different ages may also have been a factor in the bioaccumulation of PCBs: younger, smaller chicks often are fed shiners, but as they age and are able to accommodate larger fish, alewives become a larger percentage of their diet (Jablonski et al. 2005).

Zebra mussels have been implicated in the decline of several avian species that feed directly on them. Waterfowl, including buffleheads (Bucephala albeola), lesser scaups (Aythya affinis), and greater scaups (A. marila), have been shown to bioaccumulate PCBs and selenium after ingesting contaminated zebra mussels (Mazak et al. 1997). While common tern populations have declined over the last two decades it does not appear that the arrival of zebra mussels has hastened their decline. This study suggests that the fortunes of common terns as it relates to PCBs may be similar to that of the piscivorous fish that feed on alewives. Because direct monitoring and collection of adult terns is difficult and unwise given their conservation status, lake trout, which feed on alewives, may provide an indirect measure of PCB loads in common terns in the Great Lakes. 

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