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ARTICLE

Contaminant bioaccumulation dynamics in young-of-the-year bluefish subpopulations in New York Bight with a special reference to the condition and nursery area fidelity subsequent to recruitment

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Abstract: Contaminant bioaccumulation dynamics was examined in young-of-the-year (YOY) bluefish subpopulations (*Pomatomus saltatrix*) in the New York Bight ecosystem, and the results were used to assess (*i*) effects of habitat quality in terms of levels of PCBs and pesticides on bluefish condition and (*ii*) fidelity of YOY bluefish to different subestuaries that served as the nurseries subsequent to recruitment during their first summer. Total PCBs and *p*,*p*′-DDE body burdens increased with fish length, but concentrations generally increased only poorly to moderately, which suggested steady-state contaminant uptake commensurate with aggressive feeding and dilution related to rapid growth characteristic of YOY bluefish within a subestuary. High condition factors paired with elevated contamination levels in bluefish from the Lower Hudson River, as compared with bluefish from Newark Bay with poor condition factors paired with elevated contamination levels, suggested that PCBs and pesticides alone may not determine condition in these fish. We found dissimilar patterns of prominent PCB congeners in bluefish from adjacent subestuaries (e.g., Newark Bay and Lower Hudson River) suggesting separate contaminant sources. Total PCB normalized fingerprints of PCB congeners permitted statistical discrimination among YOY bluefish specimens from various estuaries with a potential to differentiate subpopulations on scales to less than 20 km. This unexpected fidelity to nursery estuaries may have implications for the management strategies.

Résumé : La dynamique de bioaccumulation de contaminants a été examinée dans des sous-populations de jeunes de l'année de tassergal (*Pomatomus saltatrix*) dans l'écosystème de la baie de New York, et les résultats ont été utilisés pour évaluer (*i*) les effets de la qualité de l'habitat, telle que mesurée par les concentrations de BPC et de pesticides, sur l'embonpoint des tassergals et (*ii*) la fidélité des jeunes de l'année à différents sous-estuaires servant de nourriceries après leur recrutement durant leur premier été. Les charges corporelles totales de BPC et de *p*,*p*′-DDE augmentent parallèlement à la longueur des poissons, mais l'augmentation des concentrations est généralement faible à modérée, ce qui indiquerait un taux constant d'absorption de contaminants reflétant l'alimentation agressive et la dilution associées aux caractéristiques de croissance rapide des targessals de l'année dans le sous-estuaire. Des coefficients d'embonpoint élevés combinés à des niveaux élevés de contamination dans les targessals du cours inférieur du fleuve Hudson, comparativement à ceux de la baie de Newark, qui présentent de faibles coefficients d'embonpoint jumelés à des niveaux élevés de contamination, donnent à penser que les BPC et les pesticides ne sont pas les seuls déterminants de l'embonpoint chez ces poissons. Nous avons noté des motifs dissemblables de congénères de BPC dominants dans des targessals de sous-estuaires voisins (p. ex. baie de Newark, fleuve Hudson inférieur), qui indiqueraient des sources de contaminants distinctes. Les empreintes normalisées de BPC totaux de congénères de BPC ont permis la discrimination statistique de spécimens de targessals de l'année de différents estuaires et pourraient permettre de distinguer des sous-populations à des échelles inférieures à 20 km. Cette fidélité non prévue aux estuaires-nourriceries pourrait s'avérer pertinente pour l'élaboration de stratégies de gestion. [Traduit par la Rédaction]

Introduction

Bluefish (*Pomatomus saltatrix*) is a highly migratory, subtropical, pelagic school species found throughout the world except for the eastern Pacific, and it is the only living species in the family *Pomatomidae* (Fahay et al. 1999; Lee 2003; Shepherd 2006). Along the eastern coast of the United States (US), bluefish commonly occurs in the estuarine and continental shelf waters from Maine to Florida. Bluefish spawn offshore in both spring and summer (Wuenschel et al. 2012). Spring-spawned young-of-the-year (YOY) bluefish enter the Middle Atlantic Bight estuaries in late-May to mid-June at 60–76 days old and a mean length of 60 mm (Able et al. 2003). In contrast, summer-spawned YOY bluefish can remain in the coastal or ocean nursery areas, or they can enter an estuary in mid- to late-August at 33–47 days old and a mean length of 46 mm. Additionally, McBride et al. (1993) reported a relatively less important autumn spawning in northeastern Florida.

In the nursery estuaries, the bluefish feed voraciously on diverse and usually abundant prey species on which they grow exponentially at rates of 0.9–2.1 mm·day^{-1} to attain sufficient size and condition for successful predator avoidance, emigration in autumn, and overwinter survival (McBride et al. 1993; Juanes et al. 1996; Able et al. 2003). However, in the course of this rapid growth, in some estuaries, YOY bluefish are potentially exposed to ele-

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vated levels of a variety of contaminants. Indeed, Williams (2006) reported that the YOY bluefish take up PCBs as soon as they enter the Hudson River estuary, and they continue to bioaccumulate PCBs throughout their nursery residence. Candelmo et al. (2010) reported significant accumulation of PCBs, pesticides, and total mercury in YOY bluefish fed with prey from relatively contaminated Hackensack River compared with prey from relatively clean Tuckerton. The authors reported that bluefish fed with contaminated prey species displayed significantly altered behavior, resulting in reduced feeding, reduced spontaneous activity, and reduced growth. Delineation of patterns of habitat utilization in YOY bluefish is thus critically important in understanding the potential for adverse health effects and ultimately the potential for recruitment to the adult stock.

Fisheries scientists have employed internal or external physical tags to examine the fidelity and movement of aquatic animals. Able et al. (2003) used internal sequential coded wire microtags to monitor the residency and movements of YOY bluefish in oceanic and estuarine habitats in the New York Bight. Although the bluefish released in the estuary were not captured in the ocean and vice a versa, the authors reported that the poor recapture rates of 0.04%–3.4% of the tagged bluefish made it difficult to discern the patterns of habitat use with this approach. Acoustic biotelemetry of Manderson et al. (2014) showed that the ultrasonically tagged YOY bluefish remained in the Navesink River, a tributary of the Hudson–Raritan Estuary, for a median of 29 days with a maximum of 52 days. Morton et al. (1993) used external tags to study the movement, growth rates, and fisheries exploitation of YOY bluefish in Moreton Bay, Queensland, Australia. The authors reported a relatively higher recapture rate of 11% probably due to the intensive fishery for this species driven by extended residence of YOY bluefish in the sheltered habitats of Moreton Bay. Physical tagging studies can be prohibitively expensive, requiring a large number of tagged specimens, albeit with questionable chances of success due to the low and unpredictable tag recapture rates.

It is apparent that novel, cost-effective methods are needed to serve as supplement, alternate, or replacement to physical tags for monitoring the movements of YOY bluefish within and across the nurseries during their summer residence. Chemical tracers that are naturally embedded in the animals via different trophic, physiological, and biochemical processes offer a potential alternative to the physical tags. As the patterns of tracer chemicals are conceptually integrated over wider spatial and temporal axes, they reflect a true and integrated image of the long-term life cycles of the test animals. Chou et al. (2002) employed the fingerprints of metal contaminants for modeling lobster migration patterns in the Inner Bay of Fundy. Ashley et al. (2003) used PCB fingerprints to study inter- and intra-estuarine differences in American eels and striped bass from the Hudson River and Delaware River estuaries. Rooker et al. (2001) used otolith elemental fingerprints to discriminate northern bluefin tuna from nursery areas in the Pacific Ocean. Takata (2004) used otolith microchemistry to examine YOY bluefish habitat utilization within the Chesapeake Bay and Maryland coastal waters. Dickhut et al. (2009) used select PCB congeners and chlorinated pesticides as tracers of bluefin tuna foraging grounds in the North Atlantic to examine the mixing of Mediterranean and western Atlantic juvenile bluefin tuna within the US mid-Atlantic Bight.

The first objective of the present study was to quantify a baseline for PCBs and chlorinated pesticides in YOY bluefish from seven subestuaries of the New York Bight ecosystem. The second objective was to examine the condition indices of YOY bluefish in differently contaminated estuaries and to understand the role of habitat contaminants such as PCBs and pesticides in influencing the condition. The third objective was to test the hypothesis that YOY bluefish from different estuaries carry different contaminant fingerprints that can be used as intrinsic marker tags in exploring the habitat utilization and fidelity of YOY bluefish.

Materials and methods

Field collection

YOY bluefish were collected using hook-and-line, seine net, or gill net from seven nursery estuaries within the New York Bight (Fig. 1), without regard to their spring- or summer-spawning histories, during mid- to late summer of 1999 to 2004. Specimens were kept on ice in the field and archived at –80 °C in the laboratory. Lengths and weights were measured, and otoliths were removed and archived from individual YOY bluefish for any future age determinations and (or) analyses of microconstituents. Sandy Hook Bay specimens collected at two locations in 2000 and 2001 were combined and analyzed as one group.

Condition factor

As the YOY bluefish diet has been reported to change with ontogeny (Juanes and Conover 1994; Scharf and Juanes 1996; Gartland et al. 2006), the type of prey item and the caloric content of those items will likely influence the condition and contaminant dynamics differently in the different growth stages of bluefish. Comparisons of condition factors (K) among bluefish specimens from different locations were therefore based on comparisons of similar presumed ages by using length as a proxy for the age. Specimens were divided after collection in two estuary groups based on their length ranges. The first group was comprised of bluefish from the Hudson River and Newark Bay with a length range of 133–160 mm. The second group was comprised of bluefish from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay with a length range of 158–189 mm. Bluefish outside of these length ranges were not considered in the condition comparisons. Navesink River bluefish were not included in the condition comparisons due to the small sample size of 5.

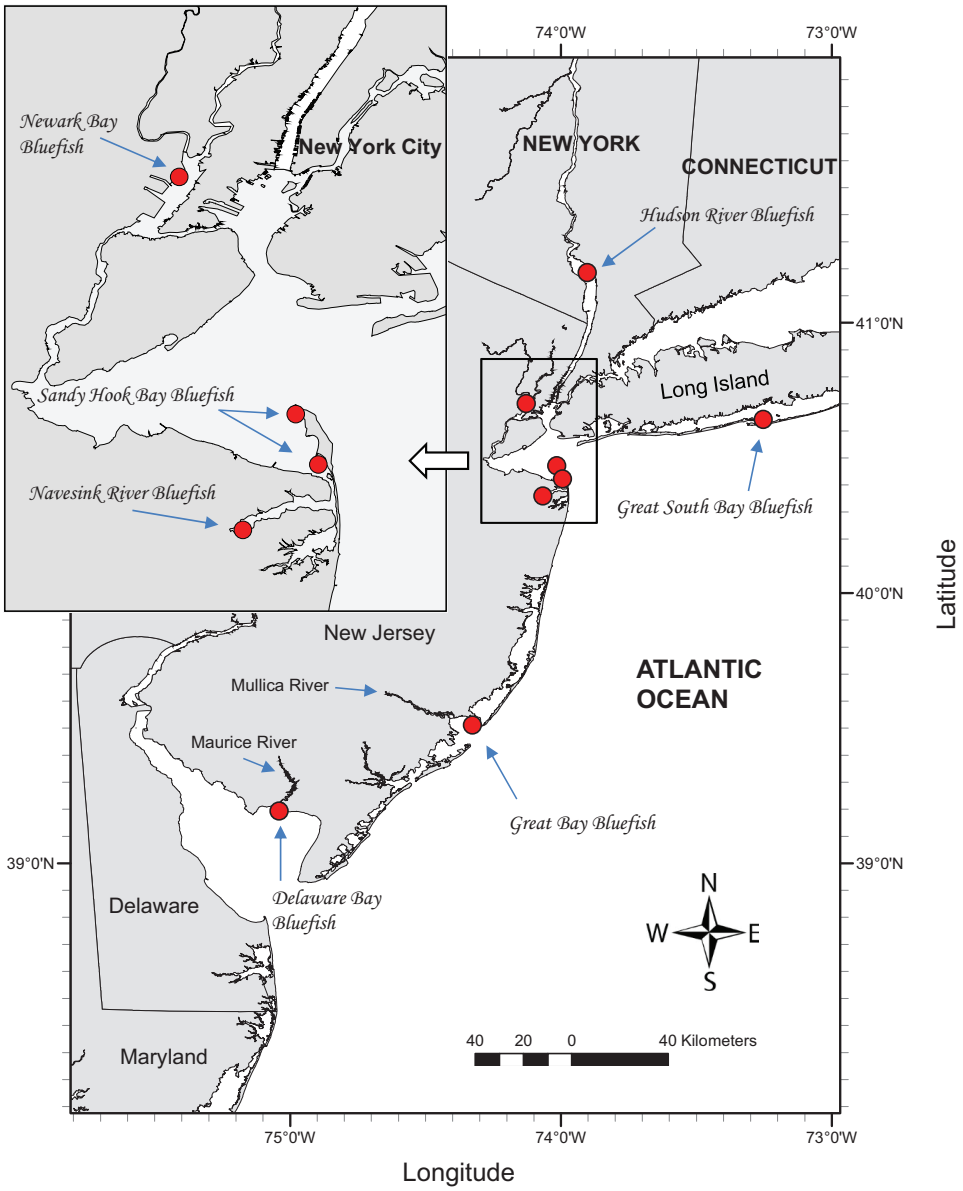
Fulton's condition factor, which assumes isometric growth, was calculated by using the expression $K = 1000W/L^3$, in which W represents the weight of the fish in grams and L represents the length of the fish in centimetres (Ricker 1975; Williams 2000).

It has been argued that the exponent "3" in the Fulton's condition factor equation does not accurately represent the length and weight relationships in a variety of fish species and that this method does not permit the comparison of results obtained from individual fish with distinct sizes (Ricker 1975; Bolger and Connolly 1989; Lima et al. 2002). As an alternative, the allometric condition factor (Lima et al. 2002) was calculated from the expression $K = W/L^b$ in which the b coefficient was estimated from the length–weight relationship equation $W = aL^b$ by regressing the natural logarithms of lengths of fish against the natural logarithms of weights. Values of the b coefficient were calculated by using two different regression methods. In the first method, the natural logarithms of lengths of specimens from all estuaries in a given estuary group were regressed against the natural logarithms of weights to give allometric condition factors using one b coefficient. In the second method, the natural logarithms of specimen lengths for each estuary were separately regressed against the natural logarithms of corresponding weights to obtain the allometric condition factors using different b coefficients for different estuaries. Parallelism of regression lines for a given estuary group was tested by using the ANCOVA homogeneity-of-slopes test.

Analyses of PCBs and pesticides

Analyses of chlorinated hydrocarbons in YOY bluefish were performed following the guidelines of Krahn et al. (1988), U.S. Environmental Protection Agency (EPA) (1993), Sloan et al. (1993), and Deshpande et al. (2000). Briefly, the individual YOY bluefish specimens were either cut into small pieces, freeze-dried, and pulverized using a blender or minced to small pieces in a blender and then manually dried with sodium sulfate using a mortar and a pestle. Method surrogate internal standards were added to the

Fig. 1. Locations of YOY bluefish collections in the New York Bight estuaries. (This figure is available in colour on the Web.)



dried and pulverized homogenates and extracted with methylene chloride in a Soxhlet extraction apparatus. Bulk interfering biological compounds were removed from the target analytes using florisil–silica–alumina glass column chromatography. Twenty percent of cleaned extract by volume was used for the gravimetric determination of lipids. HPLC surrogate internal standards were added to the extracts, and the extracts were further purified on a semi-preparative styrene–divinylbenzene polymer based size-exclusion HPLC column. Solvent of the HPLC fractions containing the target analytes was exchanged from methylene chloride to hexane. GC internal surrogate standards were added to the concentrated extracts and the extracts were analyzed for the select sets of PCB congeners and organochlorine pesticides on a DB-5 fused silica capillary column using GC-ECD. Measures of quality assurance included analyses of laboratory method blanks, analyses of internal surrogate standards, replicate analyses, analyses of standard reference materials, and participation in the international interlaboratory comparison exercises. More details of the analytical protocol are provided in the Supplementary data.[1]

Method detection limit (MDL) correction

For reporting the concentrations, half-MDL values were assigned to the analytes where the measured concentrations were below the MDL values. However, as the MDL value for a particular analyte is a statistically derived number in a separate experiment, its interpretation and its extrapolation to other samples can be subjective and perhaps erroneous. Because MDL may not accurately represent the true lower detection limit, their replacements with the half-MDL values and adoption in the statistical tests may also result in the truncating of real, low-concentration data points. Therefore, concentrations below MDL values were not adjusted in the statistical tests to allow for the detection of subtle differences between the specimens.

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfas-2015-0369.

Statistical analyses

Concentrations of PCB congeners in the individual YOY bluefish were normalized to the concentration of the most prominent and refractory PCB congener, PCB 153. The percent relative standard deviation (%RSD) values were compared for each PCB congener before and after normalization with PCB 153. The magnitude of %RSD decrease after normalization was then used as a measure of decrease in the intraestuarine data variability and consequent increase in homogeneity of PCB congener fingerprints. The candidates for this test were the concentrations of following major PCB congeners: PCBs 153, 138, 187, 180, 118, 149, 183, 95, 66, 49, and 52. Nonparametric Kruskal–Wallis ANOVA by ranks test was performed to examine statistically significant differences among concentrations of different contaminants in YOY bluefish from different estuaries (SigmaPlot/SigmaStat 10; Systat Software, Inc., San Jose, California, USA). Either Dunn's or the Holm–Sidak all pairwise multiple comparison procedure was then used to isolate the YOY bluefish group or groups that differed from the others. Discriminant function analysis (DFA) test was performed to examine the possibility of segregating subpopulations of YOY bluefish from different estuaries based on characteristic fingerprints of PCB congeners (Statistica 8.0; Statsoft, Inc., Tulsa, Oklahoma, USA). In this test, each PCB congener concentration was normalized to the sum of the concentrations of all detected PCB congeners in an attempt to remove the effects of absolute concentrations on the first principal component (Schwartz and Stalling 1991; Monosson et al. 2003; Wenning et al. 1992).

Results

Lengths and weights

Lengths (Fig. 2A) and weights (Fig. 2B) of YOY bluefish from Hudson River were lowest, and these specimens were probably youngest of all bluefish examined. Bluefish from Navesink River, Great Bay, and Delaware Bay appeared to be the oldest specimens, whereas bluefish from Newark Bay, Great South Bay, and Sandy Hook Bay were intermediate. Length ranges of bluefish selected for comparative analyses within the Hudson River – Newark Bay estuary group (Fig. 2C) were not statistically different in t tests as the power of the performed test of 0.258 was below the desired power of 0.800 (α = 0.050). Similarly, length ranges of bluefish selected for comparative analyses within the Delaware Bay – Great Bay – Great South Bay – Sandy Hook Bay estuary group (Fig. 2D) were not statistically different in one-way ANOVA as the power of the performed test of 0.119 was below the desired power of 0.800 (α = 0.050). The absence of statistical differences in the selected bluefish ranges in a given estuary group indicated the possibility of bluefish with similar age ranges in that particular estuary group and also validated the statistical comparisons of their condition factors. Weight ranges of bluefish within the Hudson River – Newark Bay estuary group (Fig. 2E) were statistically different in t tests (P = 0.004), with Hudson River bluefish being significantly heavier than Newark Bay bluefish. Weight ranges for the Delaware Bay – Great Bay – Great South Bay – Sandy Hook Bay estuary group (Fig. 2F) were significantly different in the Kruskal–Wallis one-way ANOVA test (P < 0.001). Dunn's all pairwise multiple comparison test suggested that bluefish from Great Bay were significantly heavier than bluefish from Sandy Hook Bay and Great South Bay (P < 0.05). No other statistical differences in bluefish weights were found for this estuary group.

Correlations between bluefish lengths and weights were excellent for all YOY bluefish subpopulations (Table 1). The P value of 0.5654 was well above 0.05 in the homogeneity-of-slopes test of natural log normalized length–weight regression lines for bluefish from Hudson River and Newark Bay, which suggested the parallelism of regression lines and parallel but contrasting growth rates in the two most contaminated estuaries. The graphs of natural log normalized length–weight regression lines indicated that for a given length, bluefish from Hudson River were heavier than bluefish from Newark Bay (Fig. 3A). A lower P value of 0.0193 for bluefish from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay suggested inequalities of slopes of the respective regression lines and probably nonparallel and unequal growth rates in the individual estuaries. The regression lines indicated that Great Bay bluefish were heaviest for a given length, followed in the approximate decreasing order by bluefish from Delaware Bay, Great South Bay, and Sandy Hook Bay (Fig. 3B).

Condition factors

Fulton's condition factor determination method and allometric condition factor determination method that used one b coefficient for all specimens within a given length-range-based estuary group (Lima et al. 2002) gave similar distribution patterns of individual condition factors, as well as median condition factors (Figs. 4A–4D). Although these patterns were similar, a lower b coefficient of 2.4506 for the Hudson River – Newark Bay estuary group resulted in relatively high allometric K values compared with the Fulton K value in which the exponent 3 was used in the condition factor calculations (Figs. 4A and 4B). In contrast, a higher b coefficient of 3.8034 for the Delaware Bay – Great Bay – Great South Bay – Sandy Hook Bay estuary group resulted in relatively low allometric K values compared with the corresponding Fulton K values (Figs. 4C and 4D). Patterns of Fulton's condition factors and allometric condition factors calculated as above for a given estuary group appeared to be similar to the respective patterns of bluefish weights. In t tests, the Fulton's condition factors and allometric condition factors using one b coefficient for Hudson River bluefish were significantly greater than respective condition factors for Newark Bay bluefish (P < 0.001). For the Delaware Bay – Great Bay – Great South Bay – Sandy Hook Bay estuary group, bluefish from Great Bay were generally in better condition, followed by bluefish from Delaware Bay. Bluefish from Great South Bay and Sandy Hook Bay had similar and lowest condition factors in this estuary group. Fulton's condition factors for Great Bay bluefish were significantly greater than the condition factors of bluefish from Sandy Hook Bay and Great South Bay (P < 0.05). No other significant differences were detected among Fulton's condition factors for this estuary group. Allometric condition factors using one b coefficient were significantly different for the Delaware Bay – Great Bay – Great South Bay – Sandy Hook Bay estuary group in one-way ANOVA tests (P < 0.001). The Holm–Sidak all pairwise multiple comparison procedure test indicated that allometric condition factors for Great Bay bluefish were significantly greater than allometric condition factors for bluefish from Great South Bay, Sandy Hook Bay, and Delaware Bay. No other significant differences were detected among condition factors for this estuary group. Given that bluefish length ranges within a given estuary group were approximately similar, it can be argued that fish weights were the major determinants of bluefish condition. Patterns of allometric condition factors based on different b values for different estuaries (Figs. 4E and 4F) were, however, inconsistent with the respective weight patterns and therefore these values are not discussed any further.

Lipid–length and lipid–weight relationships

Lipids were highest in bluefish from Navesink River and Delaware Bay, followed in decreasing order in bluefish from Great Bay, Sandy Hook Bay, and Newark Bay (Fig. 5). Lipids were lowest in bluefish from Hudson River and Great South Bay. Lipids correlated moderately with weights in bluefish from Newark Bay, Navesink River, and Great Bay (Table 1), and the correlations were followed in decreasing order in bluefish from Hudson River, Great South Bay, and Sandy Hook Bay. Lipid–weight correlations were not observed for bluefish from Delaware Bay (r = 0.03). Lipids correlated moderately with lengths in bluefish from Navesink River and Great Bay, and the correlations were followed in decreasing

Fig. 2. Box-and-whisker summary graphs of (A) lengths of YOY bluefish sampled from different New York Bight estuaries, (B) weights of YOY bluefish sampled from different New York Bight estuaries, (C) Fulton's condition factors for YOY bluefish sampled from Hudson River and Newark Bay, (D) Fulton's condition factors for YOY bluefish sampled from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay, (E) weights of YOY bluefish sampled from Hudson River and Newark Bay, and (F) weights of YOY bluefish sampled from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay. Values that are "far" from the middle of the distribution are referred to as outliers and extreme values. Outlier values are those values outside of the 1.5 box length range from the upper and lower values of the box. Extreme values are those values outside of the 3 box length range from the upper and lower values of the box. (This figure is available in colour on the Web.)

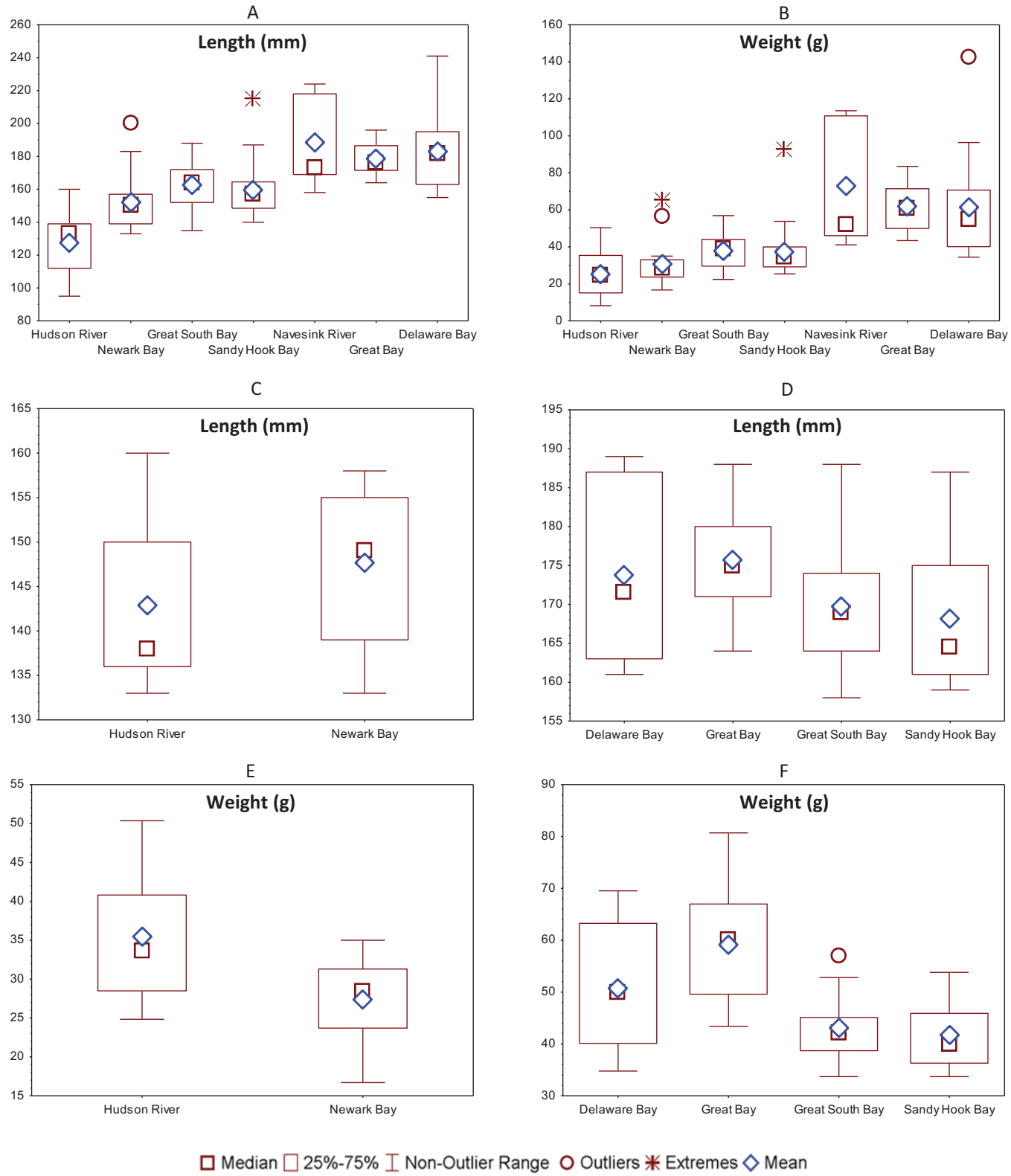
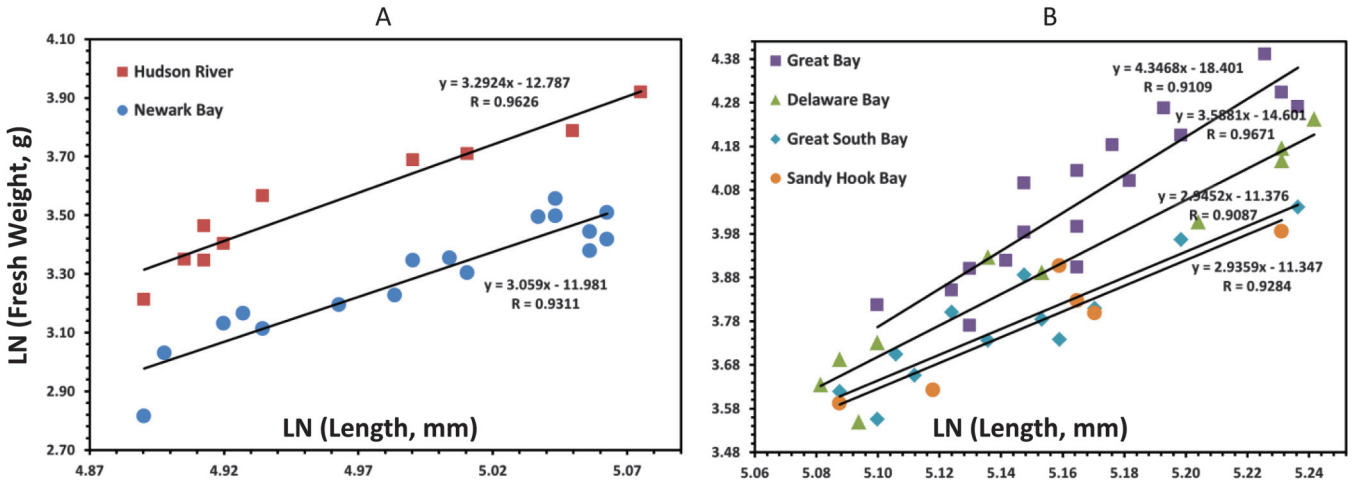


Table 1. Pearson product moment correlation coefficients (*R*) for correlations between different physical and chemical parameters measured in YOY bluefish from different estuaries in the New York Bight.

Correlation type	Hudson River	Newark Bay	Great South Bay	Sandy Hook Bay	Navesink River	Great Bay	Delaware Bay
Length–weight	0.9795	0.9329	0.9603	0.9590	0.9915	0.9253	0.9835
Length–lipids	0.5165	0.5002	0.4881	0.3287	0.6786	0.7449	0.0477
Weight–lipids	0.5350	0.7122	0.4321	0.3500	0.7168	0.7431	0.0295
Length–Fulton's condition	0.6274	0.0248	0.0107	−0.1077	0.2883	0.4080	0.4638
Length–allometric condition	0.6441	0.0435	0.0340	−0.0819	0.3392	0.4170	0.4928
Weight–Fulton's condition	0.7094	0.3493	0.2741	0.1236	0.4060	0.7185	0.5252
Weight–allometric condition	0.7241	0.3668	0.2963	0.1487	0.4543	0.7254	0.5523
Lipids–Fulton's condition	0.3294	0.6855	−0.2430	0.2541	0.5135	0.4592	0.2295
Lipids–allometric condition	0.3376	0.6947	−0.2323	0.2638	0.5400	0.4651	0.2277
Aroclors–weight	0.6479	0.3413	0.1131	−0.1379	−0.6255	0.5291	0.0483
Aroclors–length	0.7097	0.3551	0.0538	−0.1806	−0.5974	0.5291	0.1166
Aroclors–lipids	0.4332	0.3866	0.2082	0.7160	−0.8487	0.6521	0.7526
Aroclors–Fulton's condition	0.3205	0.1650	0.1371	0.1908	−0.5440	0.1860	0.0397
Aroclors–allometric condition	0.3348	0.1710	0.1383	0.1875	−0.5664	0.1907	0.0438
DDTs–weight	0.7950	0.4135	0.3362	−0.1330	−0.8028	0.5797	0.1004
DDTs–length	0.8380	0.4527	0.3112	−0.1806	−0.8028	0.6521	0.1626
DDTs–lipids	0.5989	0.3265	0.4227	0.7046	−0.2474	0.7030	0.8643
DDTs–Fulton's condition	0.3958	0.0648	0.0424	0.2418	−0.0115	0.2368	0.1153
DDTs–allometric condition	0.4122	0.0726	0.0495	0.2380	−0.0604	0.2426	0.1197
Fulton's–allometric condition	0.9998	0.9998	0.9997	0.9997	0.9986	1.0000	0.9995
Aroclors–DDTs	0.9488	0.9441	0.8409	0.9844	0.3681	0.7958	0.9555

Fig. 3. Natural log normalized length–weight relationship for (A) YOY bluefish from Hudson River and Newark Bay and (B) YOY bluefish from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay. (This figure is available in colour on the Web.)



order in bluefish from Hudson River, Newark Bay, Sandy Hook Bay, and Great South Bay (Table 1). Lengths and lipids were not correlated in bluefish from Delaware Bay.

Lipid–contaminant relationships

PCBs correlated moderately well with lipids in the bluefish from Navesink River, Delaware Bay, Sandy Hook Bay, and Great Bay (*R* = 0.6521 to 0.8488), modestly in bluefish from Hudson River and Newark Bay (*R* = 0.3865 to 0.4344), and poorly in bluefish from Great South Bay (*R* = 0.2083) (Table 1). DDTs correlated moderately well with lipids in bluefish from Delaware Bay, Great Bay, Sandy Hook Bay, and Hudson River (*R* = 0.5989 to 0.8643), modestly in bluefish from Great South Bay and Newark Bay (*R* = 0.4082 to 0.4227), and poorly in bluefish from Navesink River (*R* = 0.2474) (Table 1). As the contaminants did not correlate with lipids in bluefish from all locations, among-site comparisons using lipid-normalized data were not thought to be of significant relevance, and therefore lipid-normalized data are not discussed further.

Size–contaminant relationships

Concentrations of PCBs and DDTs increased from modestly to moderately with lengths and weights of bluefish from Newark Bay (*R* = 0.3413 to 0.4527), Great Bay (*R* = 0.5291to 0.6521), and Hudson River (*R* = 0.6479 to 0.8380) (Table 1). These relationships ranged from poor to weak in bluefish from Great South Bay, Sandy Hook Bay, Navesink River, and Delaware Bay (*R* = −0.8028 to 0.3362). As the size–contaminant relationship was not observed in bluefish from all locations, size covariate was not included in among-site comparisons.

Body weight – absolute contaminant burden relationships

Total body burdens of five major PCB congeners (PCBs 153, 138, 187, 180, and 118) and *p*,*p*′-DDE in bluefish from Newark Bay and Hudson River increased steadily with body weight, although the slopes of individual regression lines were different (Figs. 6A and 6B). The greatest slope and, thus, the greatest uptake rates were observed for the *p*,*p*′-DDE trend line for Newark Bay bluefish and

Fig. 4. Box-and-whisker summary graphs of (A) Fulton's condition factors for YOY bluefish sampled from Hudson River and Newark Bay, (B) allometric condition factors for YOY bluefish sampled from Hudson River and Newark Bay using the same "*b*" value for both estuaries, (C) Fulton's condition factors for YOY bluefish sampled from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay, (D) allometric condition factors for YOY bluefish sampled from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay using the same "*b*" value for all estuaries, (E) allometric condition factors for YOY bluefish sampled from Hudson River and Newark Bay using different "*b*" values for different estuaries, and (F) allometric condition factors for YOY bluefish sampled from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay using different "*b*" values for different estuaries. Values that are "far" from the middle of the distribution are referred to as outliers and extreme values. Outlier values are those values outside of the 1.5 box length range from the upper and lower values of the box. Extreme values are those values outside of the 3 box length range from the upper and lower values of the box. (This figure is available in colour on the Web.)

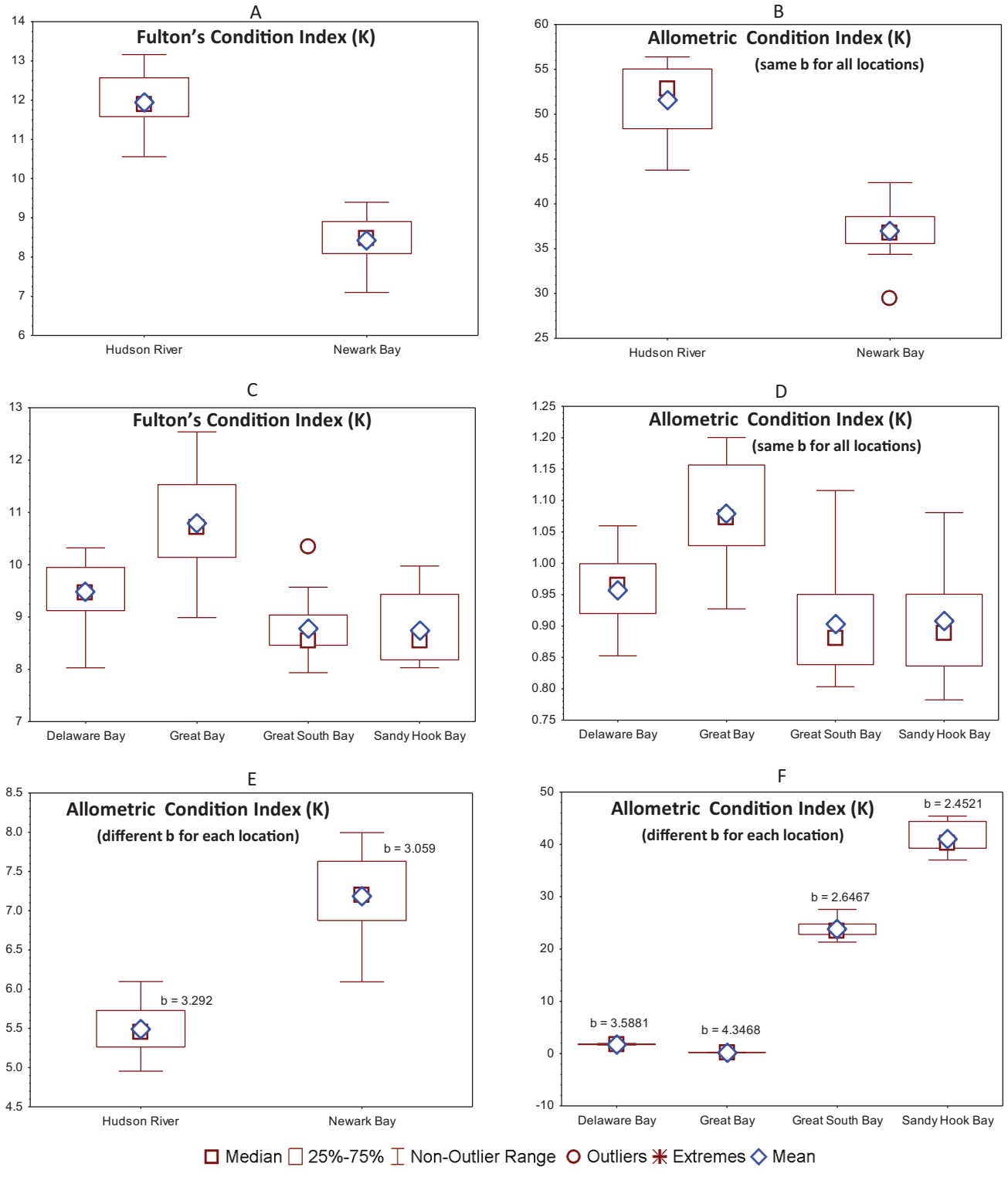
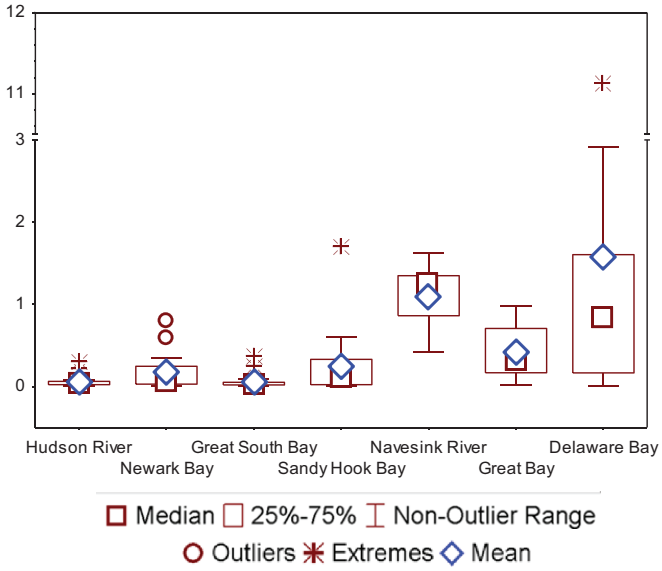


Fig. 5. A box-and-whisker summary graph of percent lipids in YOY bluefish sampled from different New York Bight estuaries. Values that are "far" from the middle of the distribution are referred to as outliers and extreme values. Outlier values are those values outside of the 1.5 box length range from the upper and lower values of the box. Extreme values are those values outside of the 3 box length range from the upper and lower values of the box. (This figure is available in colour on the Web.)



for the PCB 153 trend line for Hudson River bluefish. Despite the differential uptake of different contaminants, the *R* values were greater than 0.83 and 0.92, which suggested good correlations of contaminant body burdens with bluefish weights. A jump in body burden for different analytes was apparent for approximately 24–34 g (142–157 mm long) Newark Bay bluefish and for approximately 25–30 g (126–134 mm long) Hudson River bluefish. When the YOY bluefish PCB body burden data for all New York Bight subpopulations were pooled, the correlations between YOY bluefish weights and body burdens (Fig. 6C) ranged from poor to less than modest, with *R* values ranging from 0.0245 to 0.1732.

Body weight – contaminant concentration relationships

In contrast to body burdens, the concentrations of five major PCB congeners (PCBs 153, 138, 187, 180, and 118) and *p*,*p*′-DDE did not appear to increase in similar proportion to the body weights for the Newark Bay bluefish (Fig. 6D). Weight – contaminant concentration correlations for Hudson River bluefish ranged from poor for PCB 180 ($R = 0.11$) to moderate for *p*,*p*′-DDE ($R = 0.82$) (Fig. 6E). A slightly negative slope for the PCB 180 trend line for Hudson River specimens suggested even a slight decrease in the concentration of PCB 180. When PCB concentration data from all New York Bight YOY bluefish subpopulations were pooled, the correlations between YOY bluefish weights and concentrations (Fig. 6F) ranged from poor to modest, with *R* values ranging from 0.22 to 0.396.

PCBs and pesticides in YOY bluefish from seven different New York Bight estuaries

YOY bluefish from Newark Bay generally contained the highest contaminant concentrations regardless of whether the concentration was expressed as a mean value of (*i*) individual PCB congener, (*ii*) PCB homologue series, (*iii*) sum of all 25 PCB congeners, (*iv*) Aroclor-equivalent total PCBs, (*v*) concentrations of two major PCB congeners (PCB 153 and PCB 138), (*vi*) chlorinated pesticides, or (*vii*) concentration of a major pesticide, *p*,*p*′-DDE (Tables 2 and 3; Figs. 7A and 7B). Concentrations in Newark Bay bluefish were followed in decreasing order by the bluefish from Hudson River, Sandy Hook Bay, Great South Bay, and Navesink River. Bluefish from Great Bay and Delaware Bay were relatively uncontaminated. Similar results were obtained when the comparisons were made after the PCB data were natural logarithm normalized (Fig. 7C). Hexachloro-PCB homologs were generally found in highest concentrations at all locations and were followed in generally decreasing order by tetrachloro-PCBs, pentachloro-PCBs, and heptachloro-PCBs (for example, Fig. 7D).

Kruskul–Wallis one-way ANOVA by ranks test indicated that differences in the median contaminant concentrations among the YOY bluefish groups were greater than what would be expected by chance and that there was a statistically significant difference ($P < 0.001$). In Dunn's all pairwise multiple comparison procedure, the difference was considered significant if there was a symbol at the intersection of a horizontal line and a vertical line corresponding to a given pair of estuaries. Thus, the concentrations of PCBs in bluefish from Newark Bay were significantly different from those in bluefish from Sandy Hook Bay, Great South Bay, Navesink River, Great Bay, and Delaware Bay (Fig. 7E) (Dunn's, $P < 0.05$). The concentrations of PCBs in bluefish from Hudson River and Sandy Hook Bay were significantly different from those in bluefish from Great Bay and Delaware Bay, and the concentrations of PCBs in bluefish from Great South Bay were significantly different from those in bluefish from Delaware Bay (Dunn's, $P < 0.05$). The concentrations of *p*,*p*′-DDE in bluefish from Newark Bay were significantly different from Delaware Bay, Great Bay, Great South Bay, and Sandy Hook Bay (Fig. 7F) (Dunn's, $P < 0.05$). The concentrations of *p*,*p*′-DDE in bluefish from Hudson River were significantly different from those in bluefish from Great South Bay, Delaware Bay, and Great Bay (Dunn's, $P < 0.05$).

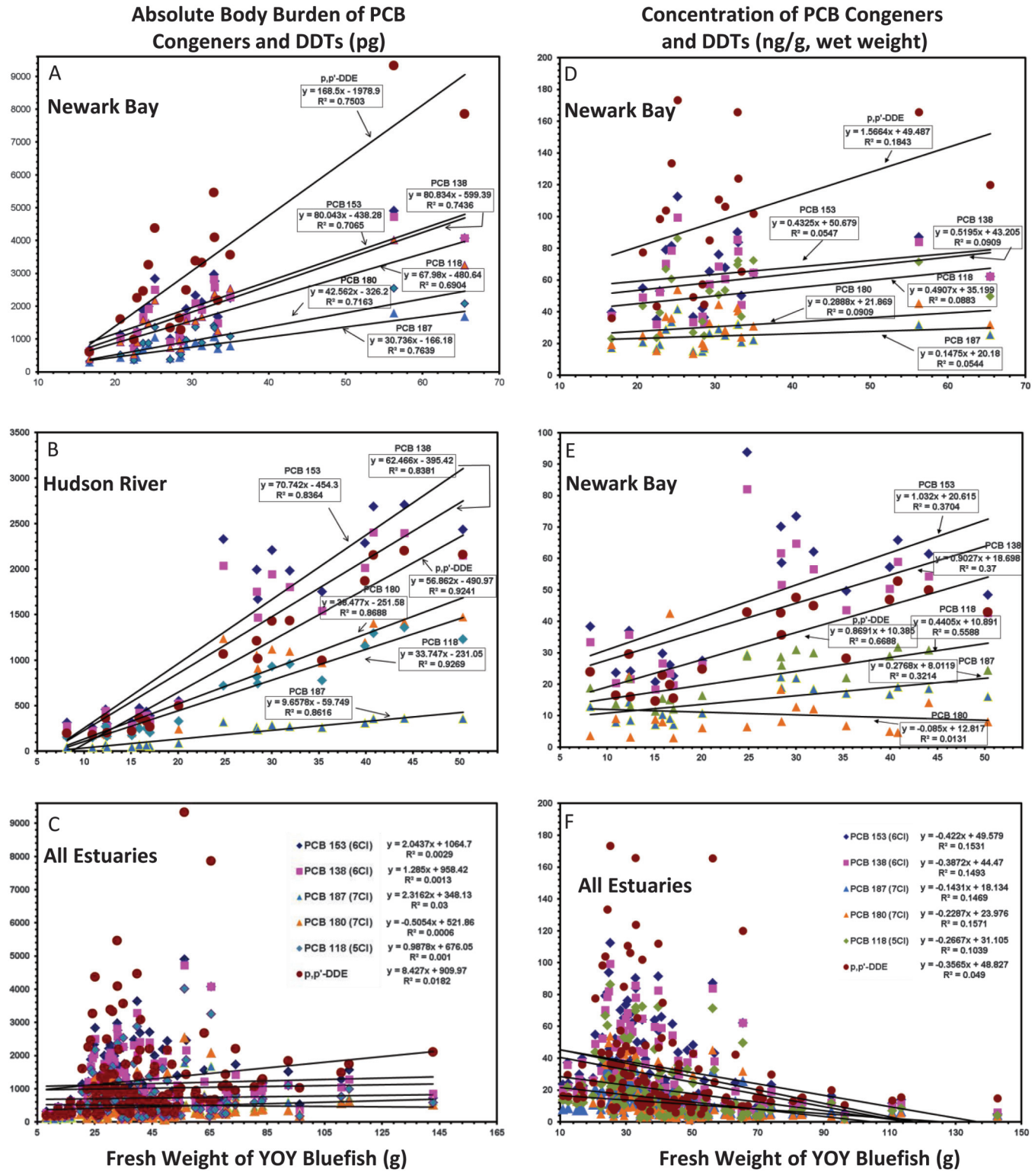
Test of homogeneity of PCB data

The %RSD values of concentrations of each of the major PCB congeners were examined as the markers of variability of contaminant exposure in different bluefish within a given estuary. Variability in concentrations estimated from %RSD values was greatest for bluefish from Sandy Hook Bay and Great South Bay, lower for bluefish from Hudson River and Newark Bay, and lowest for bluefish from Great Bay (Table 4). PCB congener data were normalized to PCB 153 to examine if there were any reductions in the noise in the original PCB data. The %RSD values of PCB 153 normalized PCB congener data was expected to provide a more realistic representation of patterns of exposure of bluefish to contaminants within a given estuary. Although PCB 153 normalization changed %RSD values very slightly for PCBs 52, 49, 95, 149, and 118 in Great Bay fish, PCB 153 normalization generally decreased intraestuarine variability in the concentrations of other major PCB congeners in Great Bay fish and for major PCB congeners in fish from other estuaries. Net decrease in %RSD was different for different PCB congeners. It was generally greatest for Sandy Hook Bay fish and lowest for Great Bay fish. Although PCB concentrations were low and similar in Delaware Bay and Great Bay bluefish, the net decrease in %RSD for Delaware Bay fish was significantly greater than that for Great Bay fish ($P < 0.001$).

Discriminant function analyses

Prominent PCB congeners in bluefish from Newark Bay in decreasing concentration order were PCBs 153, 138, 118, 149, 52, 66, 49, 180, 187, 95, and 44 (Table 2; Fig. 7D). Prominent PCB congeners in YOY bluefish from Hudson River in decreasing concentration order were PCBs 153, 138, 149, 49, 180, 52, 95, 118, 118, 187, 44, 66, and 151 (Table 2; Fig. 7D). Despite their qualitative differences, inadequate statistical discrimination between bluefish from Hudson River and Newark Bay in the Dunn's all pairwise multiple comparison procedure prompted the examination of contaminant data by the discriminant function analysis (DFA) tests.

Fig. 6. Absolute body burden – body weight relationships for 5 major PCB congeners and *p,p′*-DDE in (A) Newark Bay YOY bluefish, (B) Hudson River YOY bluefish, and (C) all YOY bluefish. Concentration – body weight relationships for 5 major PCB congeners and *p,p′*-DDE in (D) Newark Bay YOY bluefish, (E) Hudson River YOY bluefish, and (F) all YOY bluefish. (This figure is available in colour on the Web.)



In the DFA tests, the concentrations of individual PCB congeners were normalized to the sum of the concentrations of 25 PCB congeners. Partial Wilk's lambda for PCB 66 was lowest, followed in increasing order by PCBs 95, 194, 126, 187, 105, 206, 49, 138, 209, 118, 44, 18, 151, 52, 180, 153, 128, 28, 149, 195, 170, and 183. Therefore, PCB 66 was considered as the DFA variable that contributed most to discrimination of YOY bluefish subpopulations. The DFA standardized coefficients for canonical variables test indicated that the first root or the first discriminant function was weighted most heavily by PCB 49, followed in decreasing order by PCBs 194,

Table 2. MDL corrected minimum, maximum, and average concentrations (ng·g^{-1} wet weight) of individual PCB congeners, total PCBs, and total Aroclor estimates in YOY bluefish in New York Bight estuaries (SD, standard deviation).

	PCB congeners																										
	BZ 18	BZ 31	BZ 28	BZ 52	BZ 49	BZ 44	BZ 66	BZ 95	BZ 151	BZ 149	BZ 118	BZ 153	BZ 105	BZ 138	BZ 126	BZ 187	BZ 183	BZ 128	BZ 156	BZ 180	BZ 170	BZ 195	BZ 194	BZ 206	BZ 209	∑PCBs	∑Aroclors
Hudson River (*N* = 19)																											
Minimum	2.19	2.10	3.49	13.4	14.3	6.74	6.08	12.7	5.09	16.3	11.4	20.6	2.80	18.3	0.92	7.11	2.93	3.01	0.69	11.8	2.16	0.28	1.19	0.65	0.39	171	263
Maximum	6.32	8.11	10.7	40.2	47.0	17.3	15.9	41.4	16.6	54.7	31.7	93.7	8.55	82.0	4.35	29.4	12.8	13.6	5.78	49.7	9.36	2.01	5.74	2.92	1.85	587	917
Average	4.04	4.26	6.43	25.3	29.2	11.4	10.5	25.1	10.5	33.7	22.1	46.8	5.59	41.6	2.29	15.0	6.52	6.92	2.90	25.4	5.21	0.98	3.06	1.87	1.08	348	537
SD	1.38	1.90	2.17	9.47	12.0	3.71	3.58	10.4	4.18	14.4	7.37	21.2	1.79	18.6	1.01	6.11	2.76	3.12	1.31	10.8	2.19	0.47	1.28	0.75	0.42	137	210
Newark Bay (*N* = 19)																											
Minimum	2.49	0.48	2.97	8.20	8.38	4.72	7.95	10.4	8.47	20.7	23.0	35.1	7.99	32.0	1.50	15.0	6.30	4.92	2.48	13.6	5.14	1.06	3.75	2.62	1.54	262	428
Maximum	15.3	15.8	30.8	59.9	54.4	39.1	63.0	38.5	24.8	62.4	86.1	112	35.2	99.2	15.4	41.5	19.8	15.1	19.4	53.9	18.4	3.57	10.8	6.51	3.77	839	1420
Average	8.82	6.10	15.7	34.5	32.1	20.8	32.4	23.6	14.6	37.0	50.4	64.1	19.6	59.3	4.48	24.7	12.0	9.61	7.33	30.8	11.0	2.27	7.15	4.32	2.70	535	886
SD	3.82	3.74	7.40	15.0	13.7	9.18	15.2	8.36	5.07	12.5	19.3	21.7	8.58	20.2	3.41	7.41	4.21	3.42	4.34	11.2	3.86	0.78	2.28	1.13	0.65	189	314
Great South Bay (*N* = 21)																											
Minimum	0.72	0.48	1.17	1.88	1.72	1.37	1.73	1.15	0.70	1.83	2.55	8.59	0.69	6.46	0.12	4.18	1.41	1.00	0.69	2.93	0.56	0.28	1.00	0.72	0.83	46.0	38.6
Maximum	0.72	2.26	4.35	11.9	12.3	4.38	9.99	11.6	9.28	24.5	45.5	63.9	10.2	59.7	3.69	19.0	12.3	11.1	6.48	42.5	9.29	6.06	7.85	11.1	7.84	309	552
Average	0.72	0.56	1.32	2.97	2.97	1.51	2.91	4.56	4.50	11.3	15.1	27.2	3.64	22.4	0.93	9.83	4.34	3.75	2.23	10.5	3.58	1.42	2.80	3.95	3.05	148	249
SD	0.00	0.39	0.70	2.58	2.97	0.66	2.43	3.08	2.24	6.39	10.9	14.0	2.48	12.7	0.84	3.78	2.59	2.49	1.88	8.84	2.36	1.58	1.79	2.98	2.02	71.9	129
Sandy Hook Bay (*N* = 24)																											
Minimum	0.72	0.48	1.17	1.88	1.72	1.37	1.73	3.44	2.10	5.70	7.99	13.14	1.67	10.17	0.29	4.33	1.89	1.82	0.69	3.00	1.14	0.28	0.46	0.48	0.17	71.2	125
Maximum	3.09	3.76	6.36	15.35	15.89	7.86	12.35	15.71	10.10	29.15	35.47	52.24	7.65	46.74	5.00	20.51	8.54	7.28	3.67	27.17	6.84	1.19	4.03	2.48	1.34	301	497
Average	1.11	0.98	2.80	7.65	7.59	4.39	7.37	8.18	5.63	14.61	17.10	26.19	4.70	23.63	2.03	10.80	4.06	3.87	1.79	9.60	2.98	0.42	1.81	1.08	0.76	171	286
Std Dev	0.72	0.74	1.46	3.75	3.66	1.95	3.22	3.76	2.13	6.38	6.33	9.50	1.68	9.01	1.31	3.65	1.58	1.53	0.93	5.45	1.37	0.27	0.77	0.49	0.28	64.7	<103
Navesink River (*N* = 5)																											
Minimum	0.72	0.48	1.17	1.88	1.72	1.37	1.73	3.49	2.39	6.08	6.87	11.5	2.10	9.43	0.57	5.84	2.06	1.66	0.69	5.04	1.66	0.28	1.61	1.53	1.28	80.4	139
Maximum	2.89	0.97	3.58	10.1	9.30	5.82	9.05	9.75	7.04	17.2	19.9	33.8	6.93	29.6	5.11	13.9	6.24	4.43	2.56	16.3	5.70	1.36	5.08	4.37	3.09	233	387
Average	1.44	0.58	1.65	5.09	4.83	2.26	4.64	5.21	3.74	9.26	11.2	19.7	3.57	16.6	2.35	8.63	3.35	2.59	1.27	8.71	2.97	0.71	2.54	2.32	1.84	127	217
SD	1.02	0.22	1.08	3.02	2.77	1.99	2.70	2.58	1.91	4.57	5.21	8.79	2.01	8.03	1.91	3.19	1.70	1.11	0.85	4.53	1.62	0.59	1.44	1.17	0.72	61.9	100
Great Bay (*N* = 20)																											
Minimum	0.72	0.48	1.17	1.88	1.72	1.37	1.73	1.15	0.70	1.83	2.55	2.95	0.69	2.46	0.12	1.06	0.60	0.42	0.69	1.45	0.56	0.28	0.46	0.24	0.17	32.8	38.6
Maximum	2.74	0.48	1.17	1.88	1.72	1.37	3.63	2.78	2.32	6.19	8.75	16.0	2.54	13.7	0.47	7.11	2.00	2.24	0.69	6.95	1.50	0.90	1.06	0.74	0.67	81.7	163
Average	0.82	0.48	1.17	1.88	1.72	1.37	1.83	1.30	1.52	3.97	5.95	11.6	1.70	9.99	0.24	5.03	1.41	1.60	0.69	4.10	0.75	0.31	0.49	0.41	0.30	60.6	107
SD	0.45	0.00	0.00	0.00	0.00	0.00	0.42	0.45	0.66	1.71	2.24	3.09	0.60	2.76	0.12	1.32	0.46	0.44	0.00	1.37	0.33	0.14	0.13	0.19	0.14	13.7	31.9
Delaware Bay (*N* = 16)																											
Minimum	0.72	0.48	1.17	1.88	1.72	1.37	1.73	1.15	0.70	1.83	2.55	2.95	0.69	2.46	0.12	2.78	0.60	0.42	0.69	1.45	0.56	0.90	0.46	0.24	0.74	31.4	38.6
Maximum	0.72	0.48	1.17	1.88	1.72	1.37	1.73	3.03	4.48	8.52	11.4	24.6	2.99	19.2	3.65	12.9	5.06	3.84	1.80	10.8	3.46	3.61	2.05	2.25	4.01	133	232
Average	0.72	0.48	1.17	1.88	1.72	1.37	1.73	1.35	1.19	2.65	3.63	10.2	1.05	7.86	0.52	5.24	1.81	1.28	0.76	4.00	1.04	1.48	0.73	1.31	1.55	56.7	83.2
SD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	1.10	2.24	2.94	5.81	0.80	4.56	0.90	2.59	1.01	0.89	0.28	2.41	0.80	0.66	0.47	0.45	0.79	26.4	55.9
MDL determination*																											
Average	16.3	10.5	25.7	49.3	46.7	32.0	37.2	34.7	16.6	42.6	49.3	65.2	17.4	58.6	3.28	27.3	12.4	9.27	5.17	30.8	11.3	2.71	8.76	6.72	5.21	625	1010
SD	0.46	0.30	0.74	1.20	1.10	0.87	1.10	0.73	0.44	1.17	1.63	1.88	0.44	1.56	0.07	0.68	0.38	0.27	0.44	0.92	0.36	0.18	0.29	0.15	0.11	15.18	24.57
%RSD	2.82	2.90	2.89	2.42	2.35	2.72	2.96	2.12	2.67	2.74	3.29	2.88	2.53	2.67	2.27	2.48	3.09	2.91	8.51	3.00	3.17	6.51	3.32	2.24	2.13	2.43	2.43
MDL	1.44	0.96	2.33	3.76	3.45	2.74	3.47	2.31	1.39	3.67	5.11	5.91	1.38	4.91	0.23	2.13	1.21	0.85	1.38	2.90	1.13	0.55	0.91	0.47	0.35	54.9	77.2

*Method detection limit (MDL) determination using seven replicate aliquots of a homogenate of a single YOY bluefish from Newark Bay (MDL = σt, where σ is the standard deviation of the seven replicate measurements and t is the Student's t value for the six degrees of freedom (t = 3.143)), 99% confidence limit); %RSD, percent relative standard deviation.

Table 3. MDL corrected minimum, maximum, and average concentrations (ng·g^{-1} wet weight) of individual pesticides in YOY bluefish in New York Bight estuaries (SD, standard deviation).

	HCB	*b*-BHC	Lindane	Heptachlor	Aldrin	Heptachlor epoxide	Oxychlordane	*g*-Chlordane	Endosulfan I	*t*-Nonachlor	*p,p′*-DDE	*o,p′*-DDD	Endosulfan II	*o,p′*-DDT	Endosulfan sulfate	*p,p′*-DDT
Hudson River (*N* = 19)																
Minimum	0.16	0.19	0.02	0.02	0.03	0.09	0.13	0.51	14.2	1.80	14.5	1.68	0.18	1.30	0.21	0.44
Maximum	0.37	0.44	0.46	0.37	0.09	1.68	1.26	1.48	46.9	4.23	52.7	5.87	2.36	7.17	7.40	4.88
Average	0.18	0.22	0.11	0.10	0.04	1.11	0.52	0.84	28.7	2.82	32.5	3.62	0.36	4.03	3.34	1.56
SD	0.06	0.07	0.11	0.08	0.01	0.43	0.30	0.40	11.9	0.83	13.3	1.56	0.57	2.21	1.79	0.90
Newark Bay (*N* = 19)																
Minimum	0.37	0.19	0.04	0.21	0.03	0.09	0.54	2.30	18.7	4.30	36.1	3.73	1.29	1.30	0.21	1.94
Maximum	4.62	1.54	1.33	0.98	0.51	3.90	3.81	11.8	65.7	23.7	173	17.2	5.83	7.80	1.29	6.76
Average	2.29	0.69	0.29	0.53	0.26	2.17	2.21	7.92	38.6	15.0	97.9	8.61	2.70	4.04	0.80	4.47
SD	1.27	0.43	0.36	0.20	0.12	1.07	0.83	2.79	14.0	5.15	42.7	3.58	1.17	2.28	0.33	1.33
Great South Bay (*N* = 21)																
Minimum	0.16	0.19	0.02	0.02	0.03	0.09	0.13	0.51	1.46	0.70	4.26	0.43	0.18	1.30	0.21	0.44
Maximum	0.16	0.19	0.13	0.18	0.20	0.69	0.63	0.51	21.8	3.30	25.0	3.39	4.17	3.52	12.2	1.46
Average	0.16	0.19	0.05	0.06	0.05	0.25	0.25	0.51	8.92	1.64	12.4	1.70	1.17	1.56	1.27	0.64
SD	0	0.00	0.04	0.05	0.05	0.20	0.15	0.00	5.74	0.83	5.51	0.71	1.09	0.65	3.36	0.34
Sandy Hook Bay (*N* = 24)																
Minimum	0.16	0.19	0.02	0.02	0.03	0.09	0.32	0.51	1.46	1.54	4.26	1.00	0.18	1.30	0.21	0.44
Maximum	1.45	2.28	2.31	1.31	0.70	2.00	2.11	2.03	35.66	4.99	47.97	5.69	1.74	5.98	6.91	3.23
Average	0.38	0.39	0.31	0.18	0.06	0.70	0.77	1.12	14.48	3.14	25.54	2.31	0.71	2.04	1.36	1.15
SD	0.31	0.54	0.49	0.36	0.14	0.72	0.35	0.46	9.12	0.80	10.01	1.25	0.46	1.53	1.85	0.59
Navesink River (*N* = 5)																
Minimum	0.16	0.19	0.02	0.06	0.03	0.40	0.52	0.51	1.46	2.76	13.4	1.17	0.41	1.30	0.21	0.44
Maximum	0.8	0.19	1.41	0.28	0.23	1.20	1.41	3.38	8.92	7.93	74.8	2.12	3.04	1.30	0.75	5.09
Average	0.62	0.19	0.54	0.16	0.09	0.66	0.85	1.98	5.81	5.53	34.6	1.50	1.25	1.30	0.32	1.82
SD	0.26	0.00	0.61	0.08	0.09	0.32	0.35	1.15	2.74	2.37	24.7	0.39	1.10	0.00	0.24	2.08
Great Bay (*N* = 20)																
Minimum	0.16	0.19	0.02	0.02	0.03	0.18	0.13	0.51	1.46	0.70	4.26	0.43	0.18	1.30	0.21	0.44
Maximum	0.78	3.04	1.62	0.14	0.03	0.95	0.71	0.51	5.89	3.35	20.2	1.49	0.50	1.30	1.56	1.22
Average	0.21	0.44	0.29	0.04	0.03	0.42	0.24	0.51	3.75	1.39	12.3	0.91	0.20	1.30	1.02	0.56
SD	0.15	0.66	0.36	0.03	0.00	0.19	0.15	0.00	1.43	0.70	3.51	0.35	0.07	0.00	0.33	0.26
Delaware Bay (*N* = 16)																
Minimum	0.16	0.19	0.02	0.02	0.03	0.09	0.13	0.51	1.46	0.70	9.74	0.43	0.18	1.30	0.57	0.44
Maximum	1.18	0.98	0.22	0.39	0.34	2.01	0.61	1.88	7.38	4.59	42.1	6.73	0.18	2.99	3.88	3.14
Average	0.22	0.31	0.09	0.11	0.07	0.71	0.22	0.60	1.83	1.07	16.1	1.68	0.18	1.41	1.21	0.67
SD	0.26	0.24	0.07	0.10	0.09	0.53	0.16	0.34	1.48	1.07	8.50	1.49	0.00	0.42	0.80	0.68
MDL determination*																
Average	3.23	1.38	0.28	0.56	0.32	2.72	3.42	11.31	44.14	16.75	94.35	10.65	2.88	6.62	0.96	8.16
SD	0.10	0.12	0.01	0.02	0.02	0.05	0.08	0.33	0.93	0.44	2.71	0.27	0.11	0.83	0.13	0.28
%RSD	3.15	8.85	4.14	2.74	6.33	2.01	2.34	2.89	2.11	2.64	2.87	2.58	3.98	12.55	13.83	3.40
MDL	0.32	0.38	0.04	0.05	0.06	0.17	0.25	1.03	2.92	1.39	8.52	0.86	0.36	2.61	0.42	0.87

*Method detection limit (MDL) determination using seven replicate aliquots of a homogenate of a single YOY bluefish from Newark Bay (MDL = σt, where σ is the standard deviation of the seven replicate measurements and t is the Student's t value for the six degrees of freedom (t = 3.143)), 99% confidence limit); %RSD, percent relative standard deviation.

Fig. 7. Box-and-whisker summary graphs of (A) Aroclor equivalent PCB concentrations in YOY bluefish sampled from different New York Bight estuaries, (B) *p*,*p*′-DDE concentrations in YOY bluefish sampled from different New York Bight estuaries, and (C) natural log normalized Aroclor equivalent PCB concentrations in YOY bluefish sampled from different New York Bight estuaries. Values that are "far" from the middle of the distribution are referred to as outliers and extreme values. Outlier values are those values outside of the 1.5 box length range from the upper and lower values of the box. Extreme values are those values outside of the 3 box length range from the upper and lower values of the box. (D) Non-normalized concentrations of PCB congeners in terms of homologs in YOY bluefish from Newark Bay and Hudson River. Significant differences in (E) Aroclor equivalent PCB concentrations in YOY bluefish from New York Bight estuaries and (F) *p*,*p*′-DDE concentrations in YOY bluefish from New York Bight estuaries. The difference is significant if there a symbol at the intersection of a horizontal line and a vertical line corresponding to a given pair of estuaries. (This figure is available in colour on the Web.)

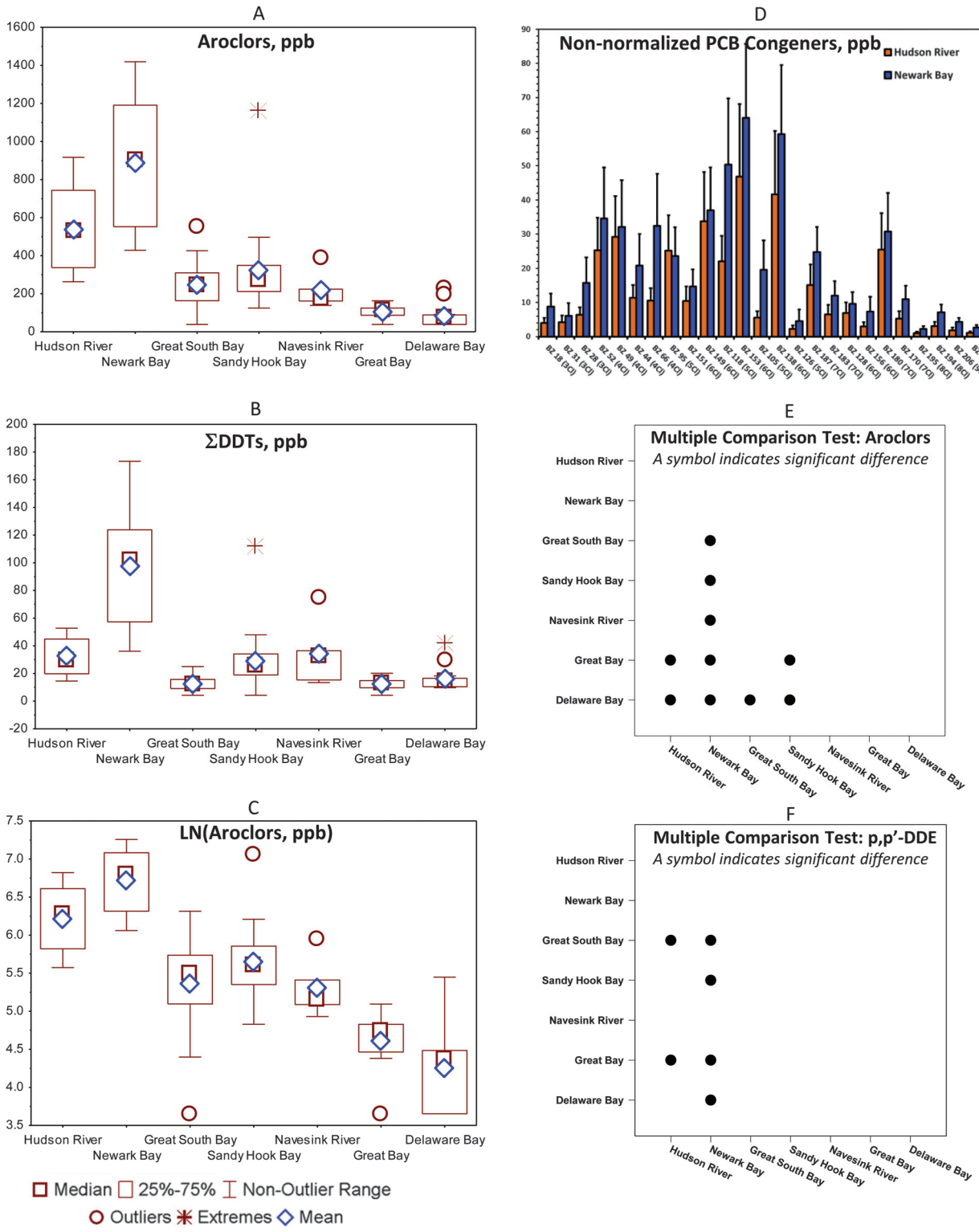


Table 4. Examination of decrease in percent relative standard deviation (%RSD) of concentrations of PCB congeners after PCB 153 normalization.

	PCB 52	PCB 49	PCB 66	PCB 95	PCB 149	PCB 118	PCB 138	PCB 187	PCB 183	PCB 180
%RSD before PCB 153 normalization										
Hudson River	37.5	41.0	33.9	41.4	42.8	33.4	44.6	40.6	42.2	42.4
Newark Bay	43.5	42.7	47.0	35.4	33.9	38.4	34.1	29.9	35.1	36.4
Great South Bay	91.6	103	75.7	62.4	55.5	69.3	56.7	38.4	59.7	83.8
Sandy Hook Bay	85.8	88.1	80.8	83.4	71.8	66.2	57.1	54.3	55.9	73.0
Navesink River	51.3	46.2	47.1	49.4	49.3	46.6	48.4	37.0	50.9	52.0
Great Bay	33.0	35.2	29.8	28.8	23.8	22.5	25.5	23.1	23.3	30.7
Delaware Bay	60.9	60.7	72.6	68.3	61.0	67.4	56.7	49.6	53.4	56.5
%RSD after PCB 153 normalization										
Hudson River	16.3	14.6	20.5	13.8	9.91	14.4	2.91	8.65	5.29	12.1
Newark Bay	29.0	27.3	32.7	19.4	9.73	14.2	4.66	9.50	8.59	9.21
Great South Bay	49.7	56.7	32.3	26.0	23.7	18.5	5.83	31.4	41.1	57.6
Sandy Hook Bay	29.3	28.0	31.4	20.1	13.7	16.8	7.83	9.62	9.70	23.4
Navesink River	27.9	26.1	23.1	27.9	13.5	10.1	3.22	8.71	8.06	7.01
Great Bay	32.2	30.7	29.7	29.6	30.7	28.9	2.94	6.90	6.14	12.2
Delaware Bay	27.5	39.0	32.3	30.4	12.9	31.7	15.9	20.0	38.1	23.6
Net decrease in %RSD after PCB 153 normalization										
Hudson River	21.1	26.3	13.4	27.7	32.9	19.0	41.7	32.0	37.0	30.2
Newark Bay	14.4	15.3	14.3	16.0	24.2	24.2	29.4	20.4	26.5	27.2
Great South Bay	41.9	46.3	43.5	36.4	31.9	50.8	50.9	7.09	18.6	26.2
Sandy Hook Bay	56.5	60.1	49.3	63.3	58.1	49.4	49.3	44.7	46.2	49.5
Navesink River	23.4	20.0	24.0	21.5	35.8	36.4	45.2	28.3	42.8	45.0
Great Bay	0.808	4.527	0.145	−0.804	−6.92	−6.35	22.6	16.2	17.2	18.5
Delaware Bay	33.3	21.7	40.3	37.9	48.1	35.7	40.9	29.6	15.3	32.9

52, 66, 44, 28, 209, 138, 128, 126, 118, 206, 153, and 149. The weightings of PCBs 195, 187, 105, 183, 170, 18, 95, and 180 to the first root were comparatively minor. The second root was weighted in decreasing order by PCBs 209, 49, 105, 206, 194, 66, 118, 149, 187, 180, 153, 28, and 126. The third root was weighted in decreasing order by PCBs 206, 138, 118, 95, 194, 52, 180, 66, 126, 153, 128, 151, 187, 105, and 149. The fourth root was weighted in the decreasing order by PCBs 138, 187, 209, 153, 180, 118, and 44.

DFA eigenvalues of the roots indicated that root 1 accounted for 53.2% of the explained variance, followed in decreasing order of 20.2% for root 2, 12.4% for root 3, 9.71% for root 4, 3.38% for root 5, and 1.14% for root 6. The cumulative proportion of explained variance or the discriminatory power for the first four roots was 95.58%. DFA means of canonical variables test indicated that, for the first root, the canonical mean of –1.39 for Newark Bay bluefish was quite different from the canonical mean of –10.09 for Hudson River bluefish, which would allow a clear distinction between the two bluefish subpopulations (Table 5). A clear distinction was noted between bluefish from Hudson River and bluefish from all other locations. The canonical means for the first root also allowed the discrimination between bluefish from Newark Bay and bluefish from Great Bay, Delaware Bay, and Great South Bay (Table 5). Canonical means for the second root allowed similar discrimination between Newark Bay bluefish and Hudson River bluefish (Table 5). The second root provided the separation between bluefish from Newark Bay and bluefish from Delaware Bay, Hudson River, Great Bay, Great South Bay, and Sandy Hook Bay (Table 5). Canonical means for the third root provided discrimination between Newark Bay bluefish and bluefish from Great South Bay, Navesink River, Sandy Hook Bay, Great Bay, and Hudson River (Table 5). Canonical means for the fourth root provided discrimination between Great Bay bluefish and bluefish from Great South Bay, Navesink River, Delaware Bay, and Newark Bay (Table 5). The fourth root also separated Great South Bay bluefish from bluefish from Sandy Hook Bay and Hudson River (Table 5).

The DFA classification matrix test indicated that bluefish from Hudson River, Newark Bay, Sandy Hook Bay, Navesink River, and Great Bay were classified to 100% accuracy to that group. Accuracy of classification was 95.2% for Great South Bay bluefish and 93.8% for Delaware Bay bluefish. A scatterplot of unstandardized canonical scores for root 2 against root 4 showed that the discriminant functions provided a clear discrimination between the most subpopulations of bluefish (Fig. 8). Navesink River bluefish appear to be discrete from Sandy Hook Bay bluefish, but this separation is not as clear as that for the other bluefish subpopulations.

Table 5. Discriminant function analysis (DFA): means of canonical variables test for PCB congeners in bluefish normalized to the sum of 25 PCB congeners.

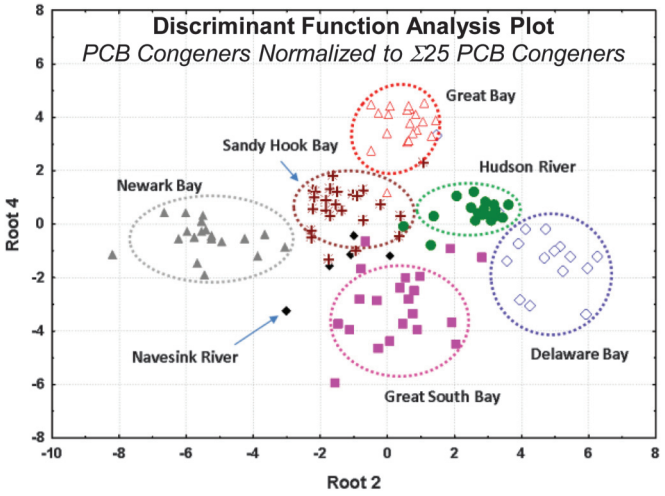
	Means of canonical variables			
	Root 1	Root 2	Root 3	Root 4
Delaware Bay	4.0567	4.57900	4.10088	−1.08250
Great Bay	4.4459	0.50028	−0.99887	3.70730
Hudson River	−10.0920	2.62615	−0.40478	0.44102
Great South Bay	2.9980	0.33864	−2.82073	−3.02248
Navesink River	−0.1071	−1.35150	−1.72615	−1.50734
Newark Bay	−1.3938	−5.37777	2.87969	−0.50536
Sandy Hook Bay	0.0827	−1.30595	−1.03308	0.64189

Discussion

Condition factors

Natural log normalized length–weight regression graphs (Fig. 3A) indicated parallel growth curves for bluefish from Hudson River and Newark Bay. However, for any given length, Hudson River bluefish were clearly heavier and, therefore, in presumably better condition than Newark Bay bluefish. This result was surprising given the notorious PCB contamination of Hudson River arising from the two General Electric plants, even though the bluefish collection site was located some 260 km away from the hot-spot source. Despite the relatively small sample size, the observed differences in the condition reflected clearly contrasting differences in the quality of two habitats. Poor to modest correlations between condition and PCBs in bluefish from Newark Bay ($r = 0.1650$) and Hudson River ($r = 0.3205$) (Table 1) indicated the importance of

Fig. 8. Groupings of YOY bluefish from different New York Bight estuaries based on discriminant function analyses of fingerprints of individual PCB congener concentrations normalized to the sum of the concentrations of 25 PCB congeners. (This figure is available in colour on the Web.)



other abiotic and biotic parameters in the explanation of fish condition. Fisk et al. (2005) reported elevated concentrations of PCBs and pesticides in Canadian arctic marine mammals that exceeded the effects thresholds, but except for the polar bears, the authors could not ascertain the evidence of stress in these populations. Other factors reported in the literature that may affect fish condition include dissolved oxygen (Dragun et al. 2013), selenium (Hinck et al. 2007), parasitic infestations (Hinck et al. 2008), and mercury (Hellyerg 2000).

Long et al. (1995) reported that Newark Bay sediments were highly toxic to the amphipod *Ampelisca abdita* compared with the relatively low toxicity of sediments from the lower Hudson River, upper New York Harbor, and portions of lower New York Harbor. The authors reported that sediment toxicity was highly correlated with concentrations of PCBs, dioxins, and pesticides, the concentrations of which often exceeded effects-based guidelines or toxicity thresholds. Litten (2003) and Litten and Fowler (1999) reported that 2,3,7,8-TCDD concentrations in the water column were 20–30 times greater in Newark Bay than in Haverstraw Bay, a location near the Hudson River YOY bluefish collection site. Similarly, mercury and cadmium concentrations in the water column were 5 and 2 times greater in Newark Bay than in Haverstraw Bay. It can only be speculated that the synergy of PCBs and pesticides with dioxins, mercury, and other less understood stress parameters in Newark Bay affected the quality of key prey species, as well as the appetite and predation success of bluefish, which resulted in their poor condition. Further assessment of cause–effect relationship is beyond the scope of this article.

Simulated growth rates of YOY bluefish

Each point on length–weight correlation graphs in Figs. 3A and 3B represents length and weight information for different individual YOY bluefish. If it is assumed that different points on this graph for a given estuary represent different developmental stages of one individual hypothetical or a synthetic YOY bluefish, then the length axis can be imagined as an age axis and the correlation graph can be viewed as a simulated growth curve. The use of length as an age proxy was based on the studies of McBride et al. (1995) and Murt and Juanes (2009). McBride et al. (1995) reported approximately linear correlations between age and fork length for bluefish specimens from Narragansett Bay sampled monthly from June to October during 1986–1992. Murt and Juanes (2009) similarly reported approximately linear correlations between age and fork length in YOY and age-1+ bluefish specimens collected in northeastern Florida in summer, autumn, and winter during 2002 and 2005. Differences in growth rates of YOY bluefish in different estuaries are likely the result of prey quality and predation success, contaminant stress, and other biotic and abiotic factors. Under these assumptions, the simulated growth rates were higher for Hudson River YOY bluefish than for Newark Bay bluefish in the Hudson River – Newark Bay bluefish group. For the Delaware Bay – Great Bay – Great South Bay – Sandy Hook Bay group, the simulated growth rates were highest for Great Bay bluefish, followed in decreasing order by specimens from Delaware Bay, Great South Bay, and Sandy Hook Bay. Growth rates for Sandy Hook Bay fish and Great South Bay fish were approximately similar. Order of growth rates and condition factors were comparable, which is not very surprising as both indicators are originally based on the length and weight data.

Test of homogeneity of PCB data

Intraestuarine variations in PCB congener concentrations in YOY bluefish may arise from (*i*) subgeographical differences in contaminant concentrations and patterns in the sediments and in prey species, (*ii*) contributions from undigested prey signatures in YOY bluefish stomach contents that were not purged before the chemical analyses for a variety of reasons ranging from the logistics of handling –80 °C frozen specimens to the potential for introducing additional unknown variables, and (*iii*) alterations in PCB signatures due to different simultaneous physiokinetic processes involving PCB congener uptake, metabolism, and elimination. Certain residual noises in the PCB congener data were expected even after PCB 153 normalization. Assuming that the diet was major route of PCB exposure, Sandy Hook Bay fish appeared to be foraging at differently contaminated trophic levels at first glance; however, PCB 153 normalization suggested that overall PCB signatures within Sandy Hook Bay were qualitatively similar (Table 4). In another case, PCB congener concentrations were low in fish from Delaware Bay and Great Bay, and we expected greater noises due to analytical variability in the measurements of low concentrations. We were surprised that the net decreases in %RSD values for Delaware Bay fish were significantly greater than those for Great Bay fish ($P < 0.001$), which suggested that analytical variability is probably less important than the natural variability arising from the biological and habitat factors. The higher natural variability of Delaware Bay bluefish than that of Great Bay fish was also evident from %RSD values before PCB 153 normalization.

Greater %RSD for Sandy Hook Bay specimens appeared to be in accordance with the collection of specimens over a wider geographical and time range. The results also suggested that contaminant concentrations in sediments in Sandy Hook Bay and (or) prey assemblages were more heterogeneous than those of the other estuaries. Improved %RSD values after PCB normalization also suggested that intraestuarine variability of PCB signatures was qualitatively and similarly low for all estuaries, with a few exceptions. Although PCB concentrations were low and similar in the Delaware Bay and Great Bay bluefish, the Delaware Bay bluefish showed relatively high specimen-to-specimen variability of PCB congener concentrations. The higher variability of PCB congener concentrations in Delaware bluefish suggested greater heterogeneity of sedimentary contaminants and (or) prey assemblages in Delaware Bay.

PCBs and pesticides in YOY Bluefish from New York Bight subestuaries

YOY bluefish specimens in the present study were collected from different estuaries in several different years. Williams (2006) reported intra- and inter-annual differences in PCB congener fingerprints in the Hudson River YOY bluefish, but these fingerprints appeared to be different from the PCB congener fingerprints in Newark Bay YOY bluefish analyzed in the present study (data not

shown). The comparison of PCB fingerprints in YOY bluefish collected from different estuaries in different years is justified as the spatial trends appear to be more important than the temporal trends.

The results of this study reflect the range of chlorinated contaminants to which YOY bluefish were exposed in subestuaries within the New York Bight (Tables 2 and 3). Concentrations of these chemicals followed the known or anecdotal contamination histories. As expected, Newark Bay and Hudson River bluefish were relatively contaminated, specimens from Sandy Hook Bay, Navesink River, and Great South Bay were moderately contaminated, and those from Great Bay and Delaware Bay were relatively less contaminated. Total body burdens of PCBs and *p*,*p*′-DDE increased with bluefish length and weight; however, the concentrations generally increased only poorly to moderately. We hypothesize that bluefish during their nursery residence are in steady-state equilibrium for contaminant uptake. Thus, although they are continually exposed to incremental contaminants in the estuary, the dilution effects related to the high growth rates qualitatively proportionately compensate for the increase in the body burden, and therefore, the concentrations change only modestly with growth.

A jump in the burden of PCBs and *p*,*p*′-DDE was apparent when bluefish from Newark Bay and Hudson River reached 138–155 mm and 125–133 mm in size. This observation may be, in part, an interesting outcome of the bluefish diet shifts with the changes in ontogeny. Juanes and Conover (1994) reported that YOY bluefish undergo habitat shift from offshore waters to inshore nursery areas at a length of about 40–70 mm, which is accompanied by a diet shift from planktivory to piscivory. The authors reported change in the diets of bluefish after their recruitment to the Great South Bay. Atlantic silverside dominated the diet (73% by weight) when the bluefish were still relatively small (98 mm). As the bluefish grew to a length of 135 mm in about 4 weeks, the diet changed to bay anchovy (34%), shrimp (21%), and Atlantic silverside (14%). The authors reported that the mean teleost prey sizes for the two sampling periods were approximately the same. Scharf and Juanes (1996) reported that YOY bluefish in the Hudson River fed on prey sizes that were smaller than those available in the environment. The authors also reported a general increase in prey size foraging with increased bluefish size across prey species bay anchovy, striped bass, Atlantic silverside, and American shad. Gartland et al. (2006) reported ontogenic shifts in YOY bluefish diet in the lower Chesapeake Bay and the coastal ocean of Virginia. Bluefish diet in May was comprised of Atlantic silverside (33.3%), fish eggs (31%), and crab zoea – megalope (16.6%). Bluefish diet in June changed to Atlantic silverside (52.1%), bay anchovy (5.4%), striped anchovy (3.8%), white perch (4%), and opossum shrimp (4.2%). The diet continued to change as the bluefish grew through November, with steady increases in the composition of bay anchovy and striped anchovy. It is possible in the present study that YOY bluefish in Hudson River displayed the diet change as they grew to 125–133 mm in length. Either the larger bluefish foraged on the same species, but more intensively, or they may have started foraging on fattier prey species such as bay anchovy and (or) menhaden at the same or distant locations. A similar analogy can be applied to the Newark Bay bluefish, except that these fish had to grow to a little larger size of 138–155 mm in length, possibly related to their suboptimal condition due to the apparently compromised habitat parameters in Newark Bay.

Role of lipids versus role of habitat in the contamination of YOY bluefish

Lipids are likely to be some of the most important contributors to the fish condition. Being nonpolar and lipophilic in nature, it is conceivable that contaminants such as PCBs and pesticides will likely bioaccumulate higher in the fattier fish. However, this is probably true only for the comparison of different fish specimens or species from a given general location. We previously reported that in New York Bight, lipids in muscle tissues were highest in bluefish, intermediate in black seabass and tautog, and lowest in summer flounder and that PCBs, DDTs, and chlordanes in these species followed the lipids trend (Deshpande et al. 2000). We also reported moderate to good correlations between PCBs and lipids for the specimens of a given species (bluefish, $R = 0.7211$; black sea bass, $R = 0.7616$; tautog, $R = 0.8124$). In another study, we reported significantly high concentrations of PCBs in YOY bluefish from different New Bedford Harbor locations (Deshpande et al. 2013) compared with PCB concentrations in YOY bluefish analyzed in the present study. We argue that when one compares fish from different estuaries, the extent of habitat contamination will perhaps play a more important role in the extent of contamination exposure of the fish than the lipid contents alone. It is therefore futile to compare lipid normalized contaminant data for fish from across different geographical locations with different or sharply contrasting contamination histories.

Grouping of YOY bluefish subpopulations

It has been documented that Hudson River receives the majority of its PCB loadings through historical inputs from the two General Electric plants in Hudson Falls and Fort Edward, New York (Brown et al. 1985; Thomann et al. 1991; EPA 2002). In contrast, Monosson et al. (2003) indicated that Newark Bay receives its PCB inventory mainly from the diverse local inputs, e.g., the contaminated rivers, industrial and municipal wastewater discharges, and shipping traffic. The authors reported site-specific differences in PCB profiles in mummichog, with Hudson River fish having greater concentrations of lesser chlorinated congeners relative to the more highly chlorinated congeners in Newark Bay fish. Lighter PCB congeners could arise from the lighter Aroclors from the General Electric contamination of the Hudson River. The heavier PCB congeners in Newark Bay could arise from the point source of heavier Aroclors in Newark Bay, or they could be associated with the greater proportion of weathered PCBs in Newark Bay. The authors concluded that PCB congener profiles among different mummichog populations likely reflected differences in the congener profiles of the PCB sources to the habitats of those populations and suggested that PCB congener profiles in organisms can be used to help distinguish PCB sources to aquatic populations. Monosson et al. (2003) provided the first direct evidence that the contaminant patterns in mummichog were different in the Newark Bay and Hudson River mummichog. The present study provides the first direct evidence that the patterns of PCB congeners and chlorinated pesticides are different in Newark Bay and Hudson River bluefish, which also substantiated the Monosson et al. (2003) suggestion that the sources of contamination in these adjacent and relatively contaminated nurseries are different. However, contrary to the results of the Monosson et al. (2003) study, the concentrations of lighter PCB congeners in bluefish from Hudson River were not greater than the concentrations of lighter PCB congeners in bluefish from Newark Bay. It remains to be investigated if the diversity and abundance of prey species is also different in the two estuaries. YOY bluefish from the two Sandy Hook Bay locations about 6 km apart clustered together in the DFA graphs, with some stray specimens, which suggested moderate, within-estuary mixing of fish within Sandy Hook Bay and possibly within other estuaries. Although not quite as clear as some of the other subpopulation groupings, PCB congener patterns in Navesink River bluefish were apparently different than PCB congener patterns in Sandy Hook Bay bluefish (Fig. 8). These two collection sites are less than 20 km apart, and the differences in PCB fingerprints may arise from the differences in local sources of PCB fingerprints in the respective habitats, as well as limited migrations away from the loosely localized nursery grounds. It was rather remarkable for a field survey to detect such unique differences in PCB fingerprints within a short geographic range. As only five fish from Navesink River were analyzed, this difference needs to be substantiated with the analyses of more speci-

mens. The fingerprint technique also distinguished bluefish specimens from various other nurseries suggesting different concentrations and patterns of contaminants in different estuaries.

In the present study, we conducted the DFA test for the PCB congener concentrations normalized to the sum of concentrations of 25 PCB congeners. The resulting groupings of some to virtually all subpopulations in DFA graphs suggested the utility of PCB congeners such as PCBs 49, 52, 66, 95, 105, 118, 138, 187, 194, 206, and 209 as potentially useful internal tags for studying site fidelity of YOY bluefish in the New York Bight subestuaries. It should be noted that these specific internal tags may be pertinent only in the context of the present data and perhaps not independently applicable in other studies as the unique contaminant patterns will likely change with the species or the habitat of concern. Increased homogeneity in intraestuarine PCB congener patterns after PCB 153 normalization suggested that bluefish within a given estuary are probably exposed to similar contaminant sources with minor to modest variations. DFA classification matrix tests classified bluefish with 100% accuracy for the Hudson River, Newark Bay, Sandy Hook Bay, Navesink River, and Great Bay. The accuracy of classification was also relatively high for the other bluefish subpopulations, with a range of 93.8%–95.2%. As only five specimens were used for the Navesink River bluefish, the DFA resolving power was expected to be limited. Surprisingly, despite the small sample size, the classification accuracy was 100% for Navesink River bluefish. Although it worked out for the Navesink River bluefish, the specimen number of 5 appears to be conceptually insufficient. However, the specimen number of about 20 seemed to be quite sufficient in identifying other different bluefish subpopulations. Inclusion of additional candidate PCB congeners to the variables, as well as other compounds to the list, may further improve the accuracy of bluefish classification, but that remains to be investigated.

Results of PCB and pesticide fingerprint analyses in the present study, results of Ca–Sr ratios in YOY bluefish otoliths in the Takata study (Takata 2004), and the tag–recapture studies of Able et al. (2003), Manderson et al. (2014), and Morton et al. (1993) corroborate the unexpectedly high fidelity of YOY bluefish for extended residences in the respective nursery subestuaries with minimal interestuarine exchange, at least within the New York Bight ecosystem. Given their high energy reserves and their highly active and migratory trait, YOY bluefish seem to be adequately capable of migrating to other estuaries. However, these movements do not seem to be necessary or bioenergetically profitable as various nursery estuaries already seem to provide plentiful prey resources to grow and offer multiple shelters to hide away from the predators. Also, given the school-fish behavior of YOY bluefish, one can speculate that such migrations away from the school network may even not be socially desirable or advantageous.

Conclusions

1. YOY bluefish from Newark Bay generally contained the highest contaminant concentrations, followed in decreasing order by bluefish from Hudson River, Sandy Hook Bay, Great South Bay, and Navesink River. Bluefish from Great Bay and Delaware Bay were relatively uncontaminated.
2. Body burden of $\sum$PCBs and *p*,*p*′-DDE increased with the length of YOY bluefish, which suggested incremental exposure during their nursery residence.
3. Contaminant concentrations generally increased only poorly to moderately, which suggested steady state of contaminant uptake resulting from the dilution of contaminants due to the rapid growth of YOY bluefish.
4. High condition factors paired with elevated contamination levels in bluefish from Lower Hudson River, as compared with bluefish from Newark Bay with poor condition factors paired with elevated contamination levels, suggested that PCBs and pesticides alone may not determine the condition in these fish.
5. Dissimilar patterns of prominent PCB congeners in bluefish from Newark Bay and Lower Hudson River suggested separate contaminant sources in these adjacent subestuaries.
6. Normalized PCB congener fingerprints permitted precise statistical discrimination among YOY bluefish specimens from various estuaries, which suggested unexpected fidelity to the nursery estuaries.

Management implications and future studies

As a result of harvest restrictions imposed under Amendment 1 to the Fishery Management Plan (FMP), bluefish are considered rebuilt as of 2009, with stock biomass above the target of 324 million pounds (Atlantic States Marine Fisheries Commission (ASMFC) 2012; National Oceanic and Atmospheric Administration (NOAA), Fisheries, FishWatch—U.S. Seafood Facts: Bluefish, http://www.fishwatch.gov/profiles/bluefish). Shepherd and Nieland (2010) reported that bluefish is currently neither overfished nor experiencing overfishing and that fishing mortality in 2009 was 0.10, below the biological reference point of 0.19. The 2014 *F* estimate of 0.141 also indicates that overfishing is not occurring and that the bluefish stock is not overfished (Stock Assessment Workshop/Stock Assessment Review Committee (SAW/SARC) 2015). The NOAA FishWatch web site suggests that although the bluefish stock has been rebuilt and is managed sustainably, several key scientific gaps need to be addressed to better inform the management. One of the important scientific gaps, in our opinion, appears to be the dearth of information on the success of contribution of YOY bluefish from differently contaminated nursery habitats to the adult bluefish stock.

Subpopulations of YOY bluefish with different health conditions leave the southern New England and Middle Atlantic estuaries in late summer to early fall and ultimately congregate into a large, southward-migrating extensive admix (Shepherd 2006). At this point, it is very difficult to identify the nursery habitat of individual bluefish or predict what percentage of the population is competent for migration and overwintering survival from a particular habitat, which complicates efforts in the recovery, conservation, and management of bluefish stock. If we could assign YOY bluefish by using PCBs, pesticides, or other suitable intrinsic tracer tags to the individual estuaries when mixed into the southward-migrating population, then the contributions of fish from the individual nursery estuaries to the total bluefish stock could be assessed. From this information, the importance and quality of different habitats in supporting a healthy and sustainable bluefish stock could be determined. Information to this level of detail about critical YOY bluefish habitats does not exist, and it is expected to be useful in the recovery and management of the decline observed in the bluefish stock (Shepherd 2006). We think that a baseline study using different chemical tracers in YOY bluefish from several nursery grounds in the Northeast and Mid-Atlantic would be beneficial. Designation of the autumn-emigrating mixed population of bluefish to their respective habitats would then help elucidate the habitat-specific recruitment processes and the effective remediation and management of potentially critical, but currently suboptimal habitats. It would also be of interest to examine whether lipid mobilization and (or) biochemical metabolic processes distort the magnitude of concentrations and (or) the integrities of chemical fingerprints in YOY bluefish from various nursery estuaries during their southward migration and overwinter residence in the southern latitudes.

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