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Article

Metabolic Disrupting Effects of Polychlorinated Biphenyls Revealed by Long-Term Temporal Variations of Lipids in Detritivorous Fish from the Rio de la Plata Basin

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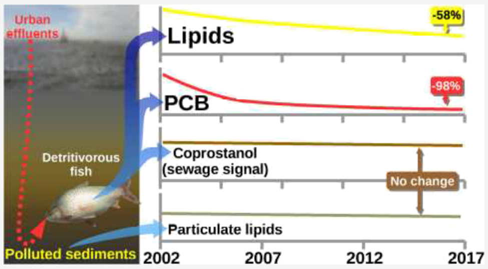

ABSTRACT: The long-term covariation (2002−2017) of lipids, polychlorinated biphenyls (PCBs), and sewage tracers was studied in the detritivorous fish (*Prochilodus lineatus*) and settling detritus from the Rio de la Plata. Fatty fish from polluted Buenos Aires area (BA) exhibited a significant decrease of muscle lipids (71 ± 12 to 29 ± 8.6% dry weight; $p < 0.0001$), triglycerides (94 to 85%, $p < 0.001$), and 18 carbon fatty acids (18C-FA: 59 ± 4.8 to 48 ± 1.4%; $p < 0.01$), reflecting a reduction of lipid accumulation, largely triglycerides enriched in 18C-FA, with a concomitant ∼20-times decline of PCBs (∼20 to >1 $\mu g\ g^{-1}$ dw). The 2017 individuals of the BA series converged with leaner and more pristine northern fish (N), which showed no significant temporal variation (20 ± 10% lipids, 67 ± 8.7% triglycerides, 41 ± 8.1% 18C-FA, and 0.22 ± 0.42 $\mu g\ g^{-1}$ dw PCB). In contrast, the fecal sterol tracer coprostanol remained abnormally higher in BA fish muscle with no significant temporal trend (120 ± 102 vs 6.6 ± 10 $\mu g\ g^{-1}$ dw or 4.4 ± 2.8 vs 0.63 ± 1.2% sterols at N). The same pattern was observed in BA settling detritus, i.e., a temporal decrease of PCBs with high, stable coprostanol concentrations denoting sustained sewage inputs, while northern detritus was enriched in plant sterols. This long-term covariation of lipids and PCBs in fish muscle from polluted BA converging with more pristine and homogeneous northern specimens while maintaining a sewage-derived diet provides rare field evidence of the declining effect of PCBs controlling the temporal variation of muscular lipids in fish.

KEYWORDS: *PCB, lipids, Prochilodus, Rio de la Plata, sewage, sterols, metabolic disrupting compounds*

■ INTRODUCTION

A growing number of recent studies highlight the importance of the environmental component underlying metabolic disorders such as diabetes and other diseases through the exposure to pollutants that act as metabolic disrupting compounds (MDC), altering general homeostasis at multiple levels.[1,2] A key consequence of the chronic exposure to MDC is the disruption of lipid metabolism leading to obesity.[3−5] MDC can exert their effects through multiple pathways, such as endocrine disruption, appetite control, and gene expression, inducing adipogenesis and lipid accumulation.[6−9] Among them, many organochlorinated compounds, especially the highly persistent and ubiquitous polychlorinated biphenyls (PCBs), were recognized as MDC, affecting lipid metabolism at transcriptional, enzymatic, and hormonal levels in laboratory experiences.[10−14]

The potential of PCBs for disruption of lipid metabolism is of particular interest given their importance as major pollutants in aquatic ecosystems worldwide, especially in urbanized areas. In the Rio de la Plata Basin, one of the largest river systems of the world, the metropolitan area of Buenos Aires is heavily polluted by urban and industrial discharges, resulting in massive historical PCB fluxes and buildup in bottom sediments.[15] Due to the high organic content of these particulate materials, the area nearby contaminated tributaries, and the main Buenos Aires sewer outfall has been selectively exploited as the feeding ground by a strict detritivorous fish, *Prochilodus lineatus* (Prochilodontidae; Characiformes).[16,17] This is the most abundant fish of the basin and has specific morpho-physiological adaptations to feed on recently settled flocculent material (suckerlike mouth, two-chambered stomach, numerous pyloric ceca, intestinal mucosal folds, etc.[18]), which facilitate the assimilation of anthropogenic organic matter and the bioaccumulation of the associated hydrophobic pollutants.[19,20] Based on compound-specific maximum daily doses and fish concentrations, a risk ranking of multiple xenobotics in this fish highlighted PCBs as the most critical residues with daily consumption limits as low as 0.1 g day^{-1}, 50 times lower than those calculated based on dioxin concentrations.[16] In a recent long-term study of PCB contamination

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in this fish, very high concentrations have been reported coincident with PCB banning in 2001−2002 (∼21 μg g^{-1} in a dry weight basis) followed by an exponential decrease, in agreement with the general reduction of PCB concentrations in settling material and sediments.[21]

The lipid composition (lipid content, lipid classes, fatty acids, and sterols) of *P. lineatus* from the Rio de la Plata shows several anomalous features, related to the opportunistic feeding on anthropogenic organic matter.[21,17,22,23] Fish from Buenos Aires were fattier than their northern, less-polluted counterparts and had a distinguishable lipid signature (in terms of fatty acid and sterol composition). Interestingly, the detailed analysis of muscle lipids suggested that the PCB content was one of the main driving factors explaining the distinctive obesity and fatty acid signature of Buenos Aires fish, suggesting a positive feedback of pollution-enhanced lipogenesis leading to facilitated pollutant accumulation in fat depots.[20,24,19,16] The combined analysis of lipids and PCB data of *P. lineatus* and settling detritus collected along 15 years in the Rio de la Plata Basin provides a unique opportunity to test the obesogen hypothesis with a large data set of field observations, which includes a significant temporal decreasing trend of PCBs.

MATERIALS AND METHODS

In this work, new and unpublished data of *P. lineatus* and settling material from the Rio de la Plata Basin have been added to previously published data to obtain longer, more representative temporal series (Table S1). *P. lineatus* was collected between 2002 and 2017 by local fishermen near the main sewer outfall of metropolitan Buenos Aires (BA; n = 166) in the Rio de la Plata estuary and at 10 northern sites along the Paraná and Uruguay rivers (N, n = 506, Figure 1). Only specimens within the 1500−3500 g body mass range were processed, amounting up to 81% of the individuals sampled during the period. For eviscerated fish, total body mass was calculated using regression equations empirically obtained for BA and N fish during the study period. After measuring the standard length and body mass, the body mass index was calculated as BMI = $100ML^{-3}$, where M is the body mass, in grams, and L is the standard length, in centimeters. A portion of dorsolateral muscle was excised and wrapped in aluminum foil, and the content of the cardiac stomach (a storage chamber without digestive activity and thus representative of the diet[25,18]) was collected when available. Samples were immediately refrigerated, transported to the laboratory, and stored at −20 °C until analysis. Settling particles were collected with fixed sediment traps deployed at 1.5 m from the surface over 12−36 h close to the sewer outfall of BA and at selected northern sites.

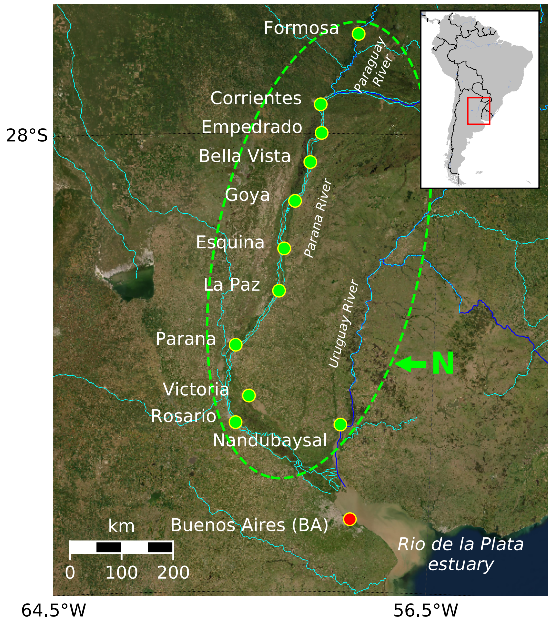

Figure 1. Sampling stations of fish in the sewer area of metropolitan Buenos Aires in the Rio de la Plata (BA, red bullet) and at multiple sites along the Paraná and Uruguay rivers (N, green bullets and dashed ellipse).

Sample Analysis. Analytical methods employed in this study have been previously reported.[22,23,20] Briefly, after solvent extraction (tissue homogenizer for muscle and sonication for settling material and stomach contents), lipids were gravimetrically determined and an aliquot of the lipid extract was saponified to separate sterols from fatty acids. Fatty acids were derivatized to their methylesthers with methanolic sulfuric acid and analyzed by gas chromatography with a flame ionization detector (Agilent 6890) and gas chromatography−mass spectrometry (Perkin Elmer Clarus 500MS). Sterols were converted to their trimethylsilyl derivatives with bis-(trimethylsilyl)trifluoroacetamide and analyzed by gas chromatography−mass spectrometry (PerkinElmer Clarus 500-MS). PCB data correspond to a previously published paper.[21]

Statistical Analysis. Numerical analysis and plots were performed in Python (version 3,8,3), using SciPy (www.scipy.org), NumPy (numpy.org), Statsmodels (www.statsmodels.org), Matplotlib (matplotlib.org), scikit-learn (scikit-learn.org), and pandas (pandas.pydata.org) libraries. Date time was converted to integer values for temporal trend analysis. Data were expressed as mean ± standard deviation. The significance of differences between two means was calculated using Student's t-test. Differences between multiple groups were analyzed by one-way analysis of variance (ANOVA) followed by a Tukey's HSD as a post hoc test for multiple pairwise comparisons between means. The relationship between continuous variables was evaluated by regression and correlation analysis, after linearization of exponential, potential, and logarithmic functions. Prediction intervals were calculated with critic values for 0.975 quantile and regression standard error. Regression confidence bands were obtained by bootstrap, resampling 500 times the residuals. To avoid the effect of time covariation when analyzing the relationship between time series variables, temporal linear trends were removed by obtaining the residuals from the regression of each variable with time, yielding time detrended relationships. The significance of Pearson's correlation coefficients (r) was evaluated using a beta distribution to get the p-value. The statistical significance level was p < 0.05 unless otherwise stated.

RESULTS AND DISCUSSION

Over the 15 years covered by this study, a clear change in lipid contents and composition was observed in *P. lineatus* from Buenos Aires metropolitan area (BA; Figure 2 A; Table S2). The most conspicuous trend is the highly significant temporal decrease of total lipids from 71 ± 12 to 29 ± 8.6% dw (t-test, p < 0.0001; exponential fit, r = −0.60; p < 0.0001). In parallel with this total lipid reduction, muscle lipid composition also

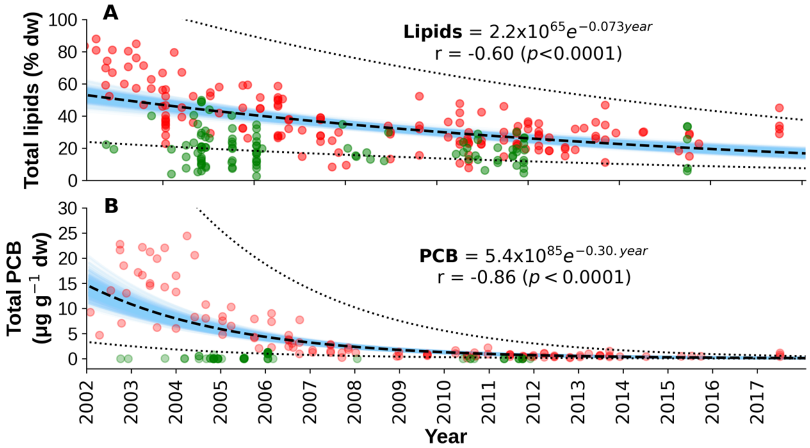

Figure 2. Temporal variation of muscular lipid content as (A) muscle dry weight proportion and total polychlorinated biphenyl (PCB) concentration, in a (B) dry weight basis concentration of *Prochilodus lineatus* from polluted Buenos Aires metropolitan area (BA, red markers) and from less-impacted northern sites of the basin (>300 km N, green markers). Regression curves and equations correspond to BA fish (no significant temporal variation was observed for N fish). The confidence band and 95% prediction interval are indicated by shaded area and dotted lines, respectively.

shows a significant change, mainly in the triglyceride abundance (Figure 3). In general, muscle lipid composition was widely dominated by triglycerides (energy storage depot) followed by phospholipids, free fatty acids, and sterols (involved in lipid bilayer homeostasis), but the BA temporal trend shows a significant decrease of the triglyceride proportion from 94 to 85% (*t*-test, $p < 0.001$), confirming that lipid accumulation is mostly driven by triglyceride di novo synthesis rather than from direct dietary uptake.[22] Notably, the temporal reduction of muscular fat depots affected the mass—length relationship evaluated through the BMI. Effectively, the BMI of BA fish shows a significant temporal decrease from 3.4 ± 0.62 to 2.5 ± 0.45 ($r = -0.47$; $p < 0.0001$; Figure S1), which is consistent with the decreasing trend of PCBs and the observation of a higher BMI in fish exposed to pollution.[26−28] In contrast to BA, fish from the less-impacted northern reaches of the basin show lower muscle lipid contents (20 ± 10% dw) and triglyceride abundance (67 ± 8.7%) with no temporal variation neither on lipids nor on BMI (Figures 2 and 3 and Figure S1). At the end of the temporal series (2015−2017), lipid and triglyceride contents of BA fish (29 ± 8.6% dw and 85 ± 15% of total lipids, respectively) tend to converge with northern fish values (21 ± 14% dw and 65 ± 12) but still remain significantly higher (*t*-test, $p < 0.01$), suggesting a progressive transition in BA fish to the characteristic biochemical composition of north fish and also to related *Prochilodus* species from nonpolluted areas of Brazil (lipids: 14−29%, triglycerides: 70−88%[29,30]).

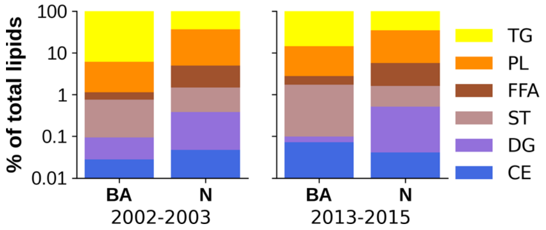

Figure 3. Temporal variation of *Prochilodus lineatus* muscle lipid class composition (as proportions of total lipids) from polluted Buenos Aires metropolitan area (BA) and from less-impacted northern sites of the basin (>300 km N) at the beginning and at the end of the study. TG: triglycerides, PL: polar lipids, FFA: free fatty acids, ST: free sterols, DG: diglycerides, and CE: steryl esters.

The well-known positive relationship between lipid abundance and bioaccumulation of hydrophobic pollutants[31,32] is particularly significant for *P. lineatus* selectively feeding on highly organic anthropogenic detritus near Buenos Aires main sewer and industrial areas. This material corresponds to settling particles collected by sediment traps and was heavily polluted with PCBs, which were thus readily incorporated in fish muscle.[33,19,20,24] Effectively, PCB contents of BA fish muscle reached maximum values in 2002 (∼20 μg g^{-1} dw), coincident with massive illegal dumping related to PCB banning in the country, and decreased ∼20-times toward 2017 (>1 μg g^{-1} dw; exponential fit, $r = -0.86$; $p < 0.0001$; Figure 2B). This trend is even more pronounced than that of total lipids and reflects the reduction of PCB usage and emissions in the area.[21] In contrast, northern fish show 2−3 orders of magnitude lower PCB burdens with no significant temporal trend (0.01−1 μg g^{-1} dw; average: 0.22 ± 0.42 μg g^{-1} dw; $p < 0.0001$). At the end of the study period (2015−2017), PCB concentrations in BA fish (0.70 ± 0.30 μg g^{-1}) were not significantly different from this N PCB average (Figure 2B). Similar PCB decreases registered in other environmental compartments indicate that this decline of PCBs in BA fish is not related to the reduction of muscular lipids, resulting in a lower affinity of superhydrophobic pollutants. Effectively, the settling detritus simultaneously collected by sediment traps also showed a decreasing temporal trend of PCBs, giving support to a general environmental reduction of these pollutants.[21] In fact, the concomitant but slower temporal decrease of lipids in fish suggests that it is linked to the reduction of PCB interference on lipid metabolism.

In this context, a deeper evaluation of the lipid composition of *P. lineatus* muscle is important to elucidate the driving factors of the observed temporal trends. Total fatty acids, accounting both for free and esterified fatty acids, are the main lipid constituents (77 ± 18% of total lipids). Overall, the fatty acid profile is dominated by 16:0 and 18:1, with a relatively low contribution of polyunsaturated fatty acids (Figure 4A). This composition was highly influenced by different environmental factors, leading to contrasting patterns between BA and

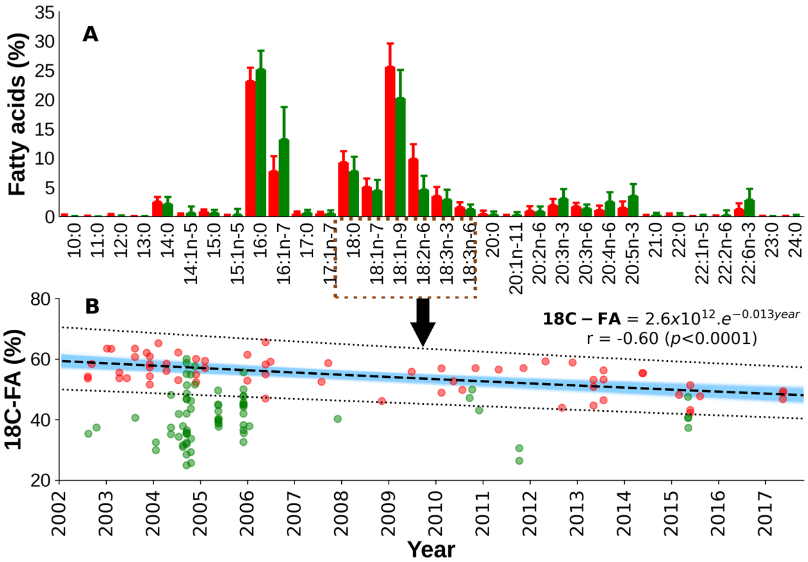

Figure 4. (A) *Prochilodus lineatus* muscle fatty acid composition (as % of total fatty acids) and (B) temporal variation of 18 carbon fatty acids (as % of total fatty acids) in Buenos Aires metropolitan area (BA, red) and in northern sites of the basin (N, green). Regression curves and equations correspond to BA fish (no significant temporal variation was observed for N fish). The confidence band and 95% prediction interval are indicated by shaded area and dotted lines respectively.

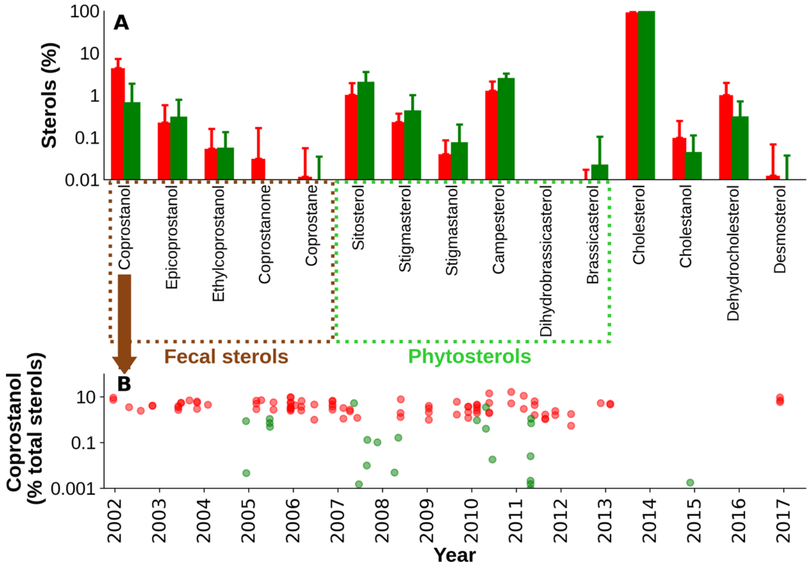

Figure 5. (A) *Prochilodus lineatus* muscle sterol composition (as % of total sterols) and (B) temporal variation of the fecal marker coprostanol (as % of total sterols) in Buenos Aires metropolitan area (BA, red) and in northern sites of the basin (N, green). Note logarithmic scales.

N. BA fish are enriched in 18 carbon fatty acids (18C-FA, 55 ± 5.6% of total fatty acids), with low contents of long-chain (≥20 carbons) polyunsaturated fatty acids (LC-PUFA, 8.5 ± 2.9%), which in *P. lineatus* are mostly derived from 18:2 and 18:3.[23] In contrast, N fish are enriched in 16 carbon fatty acids and LC-PUFA (38 ± 5.3 and 15 ± 4.9%, respectively; $p < 0.01$). The uptake of easily assimilable anthropogenic organic matter at BA could alter the fatty acid composition through muscle lipogenesis with a 18C-FA increase, but the inhibitory effect of PCBs on specific acyl desaturases and elongases would also lead to 18C-FA accumulation and PUFA decrease.[23] Laboratory experiments demonstrated that PCBs could exert these effect with doses comparable to BA muscular PCB concentrations (0.5−50 mg kg^{-1}).[34−37] Similar to lipid contents, the 18C-FA proportion of BA fish shows a temporal decrease from 59 ± 4.8 to 48 ± 1.4% (*t*-test, $p < 0.01$; exponential fit, $r = -0.60$; $p < 0.0001$; Figure 4B). Statistical analysis by stepwise downward multiple regression revealed that muscular PCB concentration was the variable that explained most of the fatty acid variability in BA *P. lineatus* muscle, supporting the hypothesis of a PCB interference on lipid metabolism.[23] In contrast, the content of 18C-FA in N fish is lower (41 ± 8.1% total fatty acids; $p < 0.001$) without any temporal trend, consistent with their residual PCB concentrations and thus irrelevant possible metabolic interference. As previously noted for lipid content and triglyceride proportions, the 18C-FA proportion of BA fish converges toward the end of the study period with N fish but still remains significantly higher (Figure 4B; *t*-test, $p < 0.001$).

Regarding the sterol composition of muscle lipids, despite the overwhelming dominance of the endogenous cholesterol (92 ± 3.5% of total sterols), *P. lineatus* has a remarkably

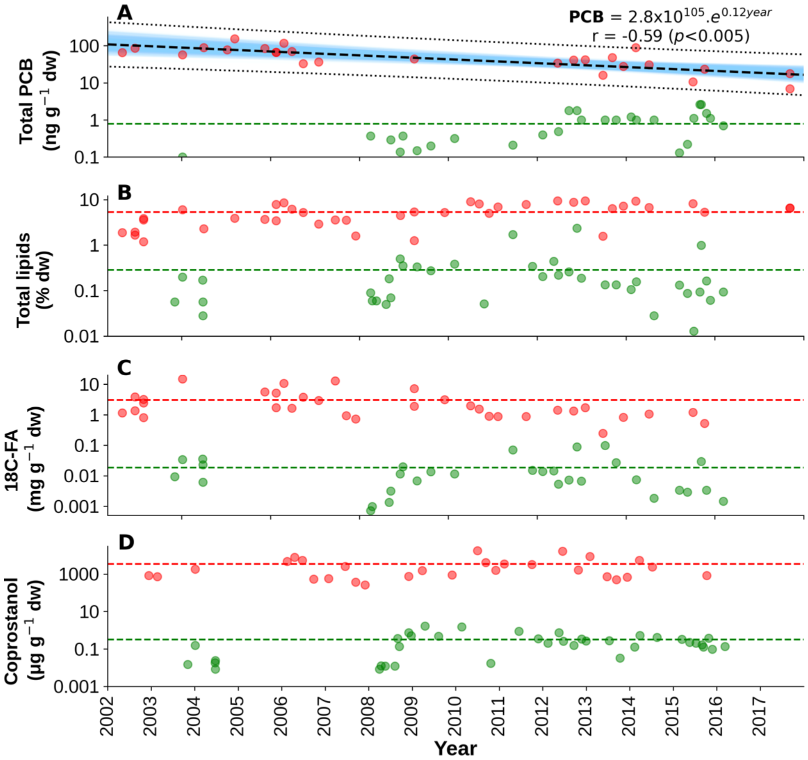

Figure 6. Temporal variation of (A) polychlorinated biphenyls, (B) lipid content (dry weight basis), (C) 18 carbon fatty acid concentration, and (D) coprostanol concentration of settling particles collected at Buenos Aires (red) and North (green). The regression curve and equation correspond to PCBs in BA (no significant temporal variation was observed for the remaining time series). The confidence band and 95% prediction interval are indicated by shaded area and dotted lines, respectively. Horizontal dashed lines correspond to time-averaged values.

diverse sterol profile compared to most bony fish,[38] including fecal and plant sterols (Figure 5A). As observed for fatty acids, muscle sterols also show contrasting patterns between BA and N fish. BA fish shows an abnormally high abundance of coprostanol (120 ± 102 μg g^{-1} dw or 4.4 ± 2.8% total sterols), a fecal marker produced by microbial degradation of cholesterol in human gut.[39] This is a reliable sewage tracer, and nonhuman sources of coprostanol (e.g., some animal feces and diagenetic reduction of cholesterol) are considered negligible in urban polluted areas.[40,41] Thus, coprostanol abundance in BA fish reflects selective feeding on sewage-derived organic detritus. In contrast, less-polluted N fish have very low coprostanol (6.6 ± 10 μg g^{-1} dw and 0.63 ± 1.2% of total sterols) and higher phytosterol contents (79 ± 42 μg g^{-1} dw and 4.8 ± 2.3% of total sterols), mainly sitosterol, campesterol, stigmasterol and stigmastanol, indicating that plant detritus is the principal food resource. In contrast with lipid and fatty acids, no significant temporal trends are observed in the sterol profile, especially for the fecal tracer coprostanol that remains consistently higher and less variable at BA (relative standard deviation: 65 vs 198% at N; Figure 5B and Table S2). The rather constant proportion of this fecal sterol at BA indicates a relatively stable input of sewage-derived detritus as the preferred food resource along the study period. This minimizes the possible significance of sewage variability (i.e., easily absorbed organic matter) that could be associated with the temporal variation of fish lipids. In fact, the detailed analysis of settling detritus intercepted by sediment traps provides a clear indication that the temporal trend of fish lipids is not linked to any change in sewage-derived food sources.

In order to evaluate whether the temporal trends observed in *P. lineatus* muscle were correlated with a concomitant dietary change, settling material was analyzed at both BA and N locations (Figure 6). In contrast to PCBs, which in BA particulates show a significant temporal decrease from 2002 to 2017 (63 ± 3.5 to 4.5 ± 0.71 μg g^{-1} dw; *t*-test, $p < 0.005$; exponential fit, $r = -0.59$, $p < 0.005$; Figure 6A), consistent with fish patterns,[21] none of the lipid parameters (total lipids, fatty acids, and coprostanol) of BA settling material show any significant temporal trend and maintain the 1−4 orders of magnitude difference with N detritus throughout the whole study period. Settling material from BA is mainly anthropogenic and highly organic compared to vegetal-derived detritus at N, which contained only trace amounts of PCBs without any clear temporal trend (0.79 ± 0.73 ng g^{-1} dw). In fact, BA settling material is enriched in lipids (5.3 ± 2.6 vs 0.28 ± 0.46% dw at N, *t*-test, $p < 0.0001$) with higher 18C-FA contents (3.1 ± 3.6 vs 0.019 ± 0.025 mg g^{-1} dw, *t*-test, $p < 0.0001$; Figure 6B,C). The massive inputs of fresh and sewage-derived organic matter at BA result in extremely high coprostanol concentrations in settling detritus, and its temporal variation was largely related to particle vertical flux and river discharge, resulting in cyclic seasonal variations with no long-term temporal pattern.[42] Thus, coprostanol concentration in settling material maintained a four-order of magnitude difference between BA and N (3432 ± 4476 vs 0.32 ± 0.38 μg g^{-1} dw, $p < 0.0001$) throughout the study period (Figure 6D). The stomach content composition of *P. lineatus* provides additional evidence confirming that *P. lineatus* feeds on this sewage-derived particulate material. A clear similitude between the *P. lineatus* stomach content and settling material composition at BA was previously observed in terms of proximate composition, lipid class profile, and fatty acids.[17,22,23] The sterol profile also reflects this similitude;

coprostanol is the major constituent of the stomach contents of the fish (53% of total sterols, Figure S2), very similar to the settling material and the sterol composition of human feces.[42] Contrasting with the massive contribution of sewage-derived material to *P. lineatus* diet at BA, the stomach contents from N fish were dominated by plant sterols and endogenous cholesterol, reflecting preferential feeding on natural vegetal detritus, which is the typical diet of this fish in nonpolluted environments.[18]

The lipid content and composition of fish results from the complex interaction of multiple physiological and environmental variables, such as food availability and quality, gender, growth, reproductive status, seasonality, temperature, etc. Thus, in order to evaluate the effect of these factors, the temporal variation of environmental and biological parameters was tested for the study period. Temperature in the Rio de la Plata Basin remained fairly stable during the study period except for an increase at the end of the period in the Paraná River, where nevertheless the lipid composition of N fish remained stable (Figure S3). River flow in the Rio de la Plata Basin has a complex and cyclical temporal behavior related to regional and large-scale climatic processes like ENSO[43] (Figure S4) and has no relationship with the long-term decreasing temporal trends observed both for PCBs and lipid parameters in *P. lineatus*. The body mass, a variable previously identified as one of the main drivers of *P. lineatus* lipid content,[22] was limited to the 1500−3500 g range and did not exhibit any temporal sampling bias, averaging 2444 ± 993 g throughout the study period (Figure S5). In addition to the influence of body mass, lipids may differ between males and females and may be susceptible to seasonal variations. However, no significant differences were found in terms of lipid content between males and females nor between seasons, and no temporal trends associated with gender or season were observed (Figure S5).

Therefore, ruling out these variables and the variation of sewage discharges as possible drivers of the temporal trend of *P. lineatus* lipids, our temporal data strongly point to a decreasing interference of PCBs on lipid metabolism in this fish. In fact, muscle lipid content is highly correlated with PCBs, even after time detrending of these variables in order to avoid spurious relationships due to temporal covariation (lineal fit, $r = 0.74$, $p < 0.0005$; Figure 7). There is a growing burden of data evidencing the metabolic disrupting effect of PCBs and other hydrophobic pollutants, which could promote metabolic disorders and obesity. Several studies, carried out mostly in rodents, have found that PCBs can promote lipid accumulation through multiple ways, such as lipid oxidation inhibition, overexpression of lipid biosynthesis genes, interaction with gut microbiota, expression of proinflammatory cytokines, lipase suppression, adipokine development, and interference with thyroid hormones.[8,10,44,45,13,46] The effect of PCBs on lipid homeostasis in fish is less known, but increased PPARγ expression, up regulation of enzymes of the fatty acid synthesis pathway, and adipogenesis have been reported for PCB-exposed fish (2−8 mg kg^{-1}).[47,48] Disruption of lipid metabolism and body mass gain were observed in zebrafish exposed to a mixture of PCBs and other organic pollutants.[49] Adeogun et al.[50,51] found evidence of an obesogenic effect of PCBs and PAH (whose concentrations were correlated with PPAR expression and body mass index), in fish from polluted African freshwaters. Similarly, disrupting effects of PCBs on lipid metabolism, through enhanced PPAR transcription and liver steatosis, were observed in Mediterranean Bluefin tuna[52] and in captivity-reared zebrafish.[53] However, the possible consequences of PCB interference on lipid homeostasis over long-term periods remain unexplored, despite well-documented temporal variations of these pollutants in fish.[54−57]

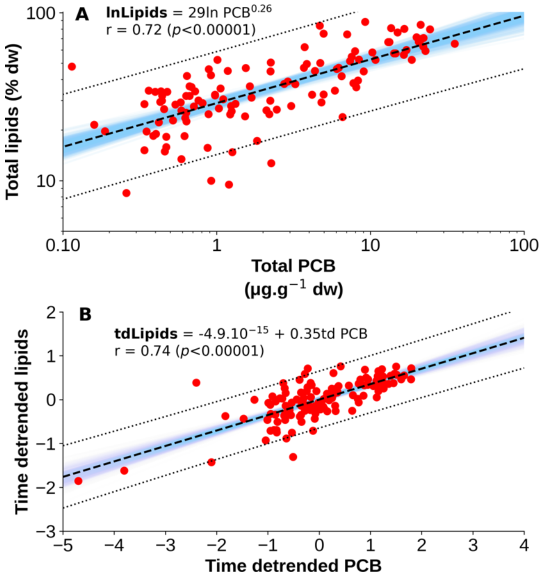

Figure 7. (A) Relationship between polychlorinated biphenyls (PCB) and lipid contents in *Prochilodus lineatus* muscle from Buenos Aires. (B) Time detrended relationship between the residuals of the regressions of total lipids (tdLipids) and PBC (td PCB) relationships with time. The confidence band and 95% prediction interval are indicated by shaded area and dotted lines, respectively.

Overall, our long-term field data point to PCBs as a key factor affecting the lipid content and composition of *P. lineatus* from the heavily polluted Buenos Aires area. The extremely high PCB concentrations in fish at the beginning of the study coincide with an unusually high lipid accumulation in muscle, with a distinctive fatty acid signature. The sharp decrease in muscle PCBs was accompanied by a concomitant less pronounced change in the lipid content and composition. Toward the end of the study, the PCB concentration, lipid content, and fatty acid composition of BA fish tend to converge with more pristine northern specimens. However, BA fish still remains fattier, reflecting a richer diet based on anthropogenic organic matter at Buenos Aires instead of organic-poor vegetal detritus, which is the principal food resource for nonpolluted northern fish.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c02299.

> Two tables and five figures with yearly averaged lipid composition, body mass index variation, stomach content composition, and temporal variation of environmental and biological factors (PDF)

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Notes

The authors declare no competing financial interest.

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