

1 Supplementary Material and Methods for **Repeated measures of**
2 **mercury concentrations demonstrate persistent territory-**
3 **level contamination and stable individual differences in**
4 **exposure in a riverine bird predator**

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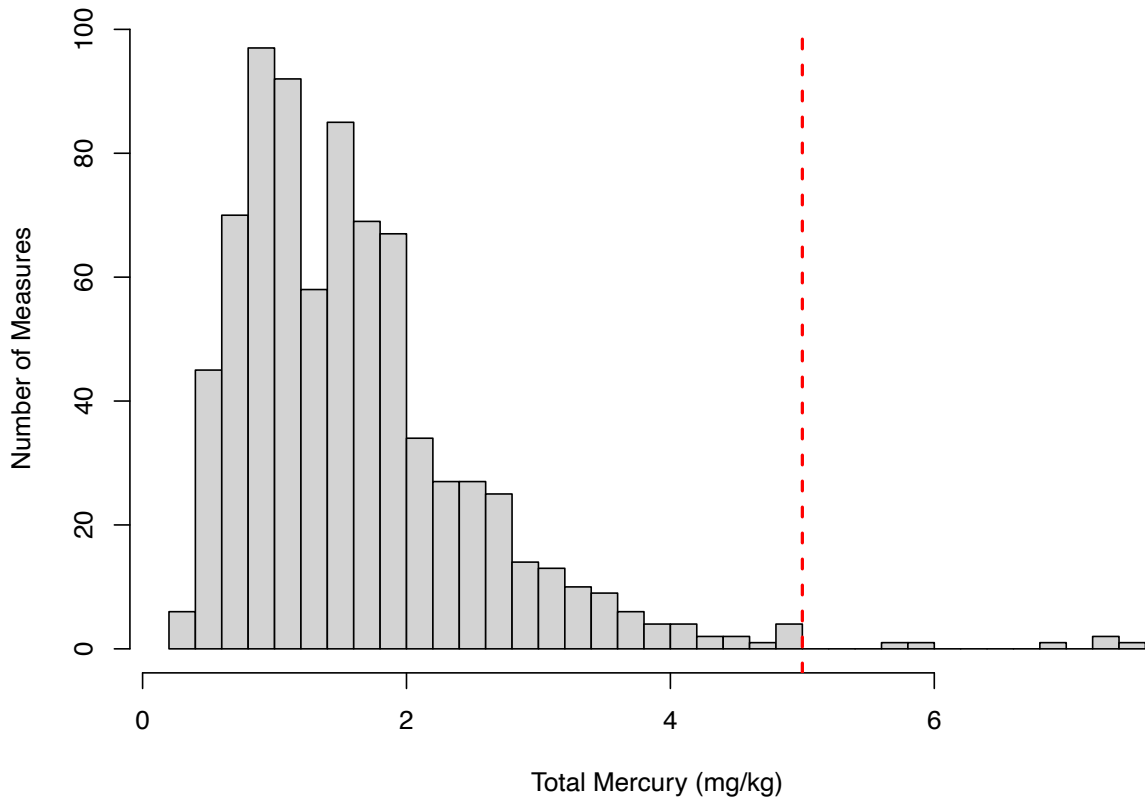
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Supplementary methods: Mercury in the dipper population



Supplementary Fig. S1 Distribution of total mercury concentrations in feathers of adult female white-throated dippers (*Cinclus cinclus*) in the Chartreuse mountains, France (N = 777 measures from 451 individuals, 2017–2025). The distribution is highly right-skewed; mean $\pm$ SD feather mercury was 1.62 ± 0.95 mg·kg⁻¹ dry weight, ranging from 0.27 to 7.54 mg·kg⁻¹. The dashed red line marks the approximate 5 mg·kg⁻¹ threshold above which feather mercury burdens are considered indicative of elevated exposure in birds (Burger & Gochfeld, 1997).

Supplementary Methods: Repeatability and variance partitioning

In addition to the single-factor and full four-factor random-effects models reported in the main text (Table 1), we fitted all intermediate two- and three-factor combinations of individual, territory, river, and year as random intercepts on log-transformed feather mercury concentrations, using the rptR package (Stoffel et al., 2017). Models were compared using Akaike's Information Criterion (AIC); the full four-factor model (individual + territory + river + year) had the lowest AIC among all 15 candidate structures and was retained for variance partitioning in repeatability analyses in the main text.

Supplementary Table S1. Repeatability estimates (R and 95% confidence intervals) and model comparison statistics (AIC, BIC, Δ AIC) for all 15 possible combinations of individual, territory, river, and year as random intercepts on log-transformed feather mercury concentrations, ranked by AIC. The full four-factor model (bold) had the lowest AIC.

Model	Individual	Territory	River	Year	AIC	Δ AIC
Individual + Territory + River + Year	0.42 [0.31, 0.55]	0.12 [0.06, 0.20]	0.26 [0.06, 0.43]	0.04 [0.00, 0.08]	730	0
Individual + River + Year	0.50 [0.40, 0.66]	—	0.27 [0.08, 0.42]	0.04 [0.00, 0.09]	750.9	20.9
Individual + Territory + River	0.43 [0.31, 0.55]	0.13 [0.08, 0.22]	0.27 [0.10, 0.43]	—	752.6	22.6
Individual + River	0.52 [0.39, 0.66]	—	0.29 [0.11, 0.44]	—	775.8	45.8
Individual + Territory + Year	0.48 [0.38, 0.60]	0.32 [0.20, 0.41]	—	0.05 [0.01, 0.12]	817.4	87.4
Individual + Territory	0.50 [0.42, 0.60]	0.34 [0.25, 0.43]	—	—	842.8	112.8
Individual + Year	0.75 [0.67, 0.81]	—	—	0.06 [0.01, 0.13]	879.2	149.2
Territory + River + Year	—	0.22 [0.15, 0.30]	0.28 [0.09, 0.44]	0.05 [0.00, 0.11]	910.4	180.4
Individual only	0.80 [0.76, 0.84]	—	—	—	912.4	182.4
Territory + River	—	0.23 [0.16, 0.34]	0.30 [0.10, 0.45]	—	948.8	218.8
River + Year	—	—	0.29 [0.08, 0.46]	0.05 [0.01, 0.10]	990.4	260.4
Territory + Year	—	0.50 [0.43, 0.56]	—	0.06 [0.01, 0.12]	1007.9	277.9
River only	—	—	0.31 [0.12, 0.46]	—	1033.9	303.9
Territory only	—	0.53 [0.47, 0.60]	—	—	1050.2	320.2
Year only	—	—	—	0.08 [0.02, 0.21]	1218.1	488.1

Supplementary methods: Landscape Analysis

Landscape PCA and composite urbanisation axis

To reduce collinearity among correlated territory-level landscape variables and to derive a composite index of local human impact, we performed a principal component analysis (PCA) on four standardized landscape variables measured around each territory: (i) percent urban land cover, (ii) percent agricultural land cover, (iii) total surface of buildings (each measured within an elongated buffer following the river channel, extending 500 m along the watercourse and 250 m from the bank, centred on the nest), and (iv) number of inhabitants in the municipality in which each territory is located. All variables were centred and scaled to unit variance prior to analysis.

Territory buffers were intersected with CORINE Land Cover 2018 (Copernicus Land Monitoring Service; Büttner et al., 2014; Copernicus Land Monitoring Service, 2018) to obtain the percentage of land cover classified as urban and agricultural use. Demographic information (number of inhabitants per municipality) was obtained from French national census statistics (INSEE, 2023), while building surface was taken from the national topographic database BD TOPO® (IGN, 2023). Altitude for each territory was taken as the elevation at the associated nesting site, extracted from the national digital elevation model BD ALTI® (IGN, 2021). Details of data sources and extraction protocols are provided in Supplementary Table S2.

The first principal component (PC1) explained 64.0% of the total variance and represented a gradient from low-human impact territories to more urbanised territories, with higher scores associated with a higher number of inhabitants in the municipality, plus greater building surface and higher urban land cover around the territory (Supplementary Tables S3–S4). We defined PC1 as a composite ‘human footprint index’ (HFI_{territory}) and used this score as the only PCA-derived predictor in the primary mixed-effects model of log-transformed feather mercury concentrations presented in the main text. The second principal component (PC2) explained a further 18.0% of the variance and was driven primarily by agricultural land cover; number of inhabitants loaded moderately on PC1 and only weakly on PC2, with its strongest loading occurring on the lower-order PC3 (Supplementary Table S4), consistent with its coarser (municipality-level) spatial resolution relative to the other variables. Although PC2 was not included in the primary model, we additionally tested a model including PC2 alongside PC1 to confirm that the human footprint effect was not sensitive to this choice (Supplementary Table S8).

Eigenvalues and percentages of variance explained for the first four principal components are given in Supplementary Table S3. Variable loadings (correlations between original variables and the first three

72 principal components) are summarised in Supplementary Table S4. A variable-correlation biplot is
73 provided in Supplementary Fig. S2.

74 **Supplementary Table S2.** Sources, definitions, units and spatial scales of landscape variables used in the territory-level PCA, as fixed effects in
75 linear models, or as a validation benchmark. Most variables were extracted within an elongated buffer following the river channel (approximately
76 500 m along the watercourse by 250 m from the bank, centred on each territory's nest); exceptions are number of inhabitants (municipality-level),
77 altitude (point elevation), and the Global Human Footprint Index (1 km resolution), as detailed in the Unit/Scale column below.

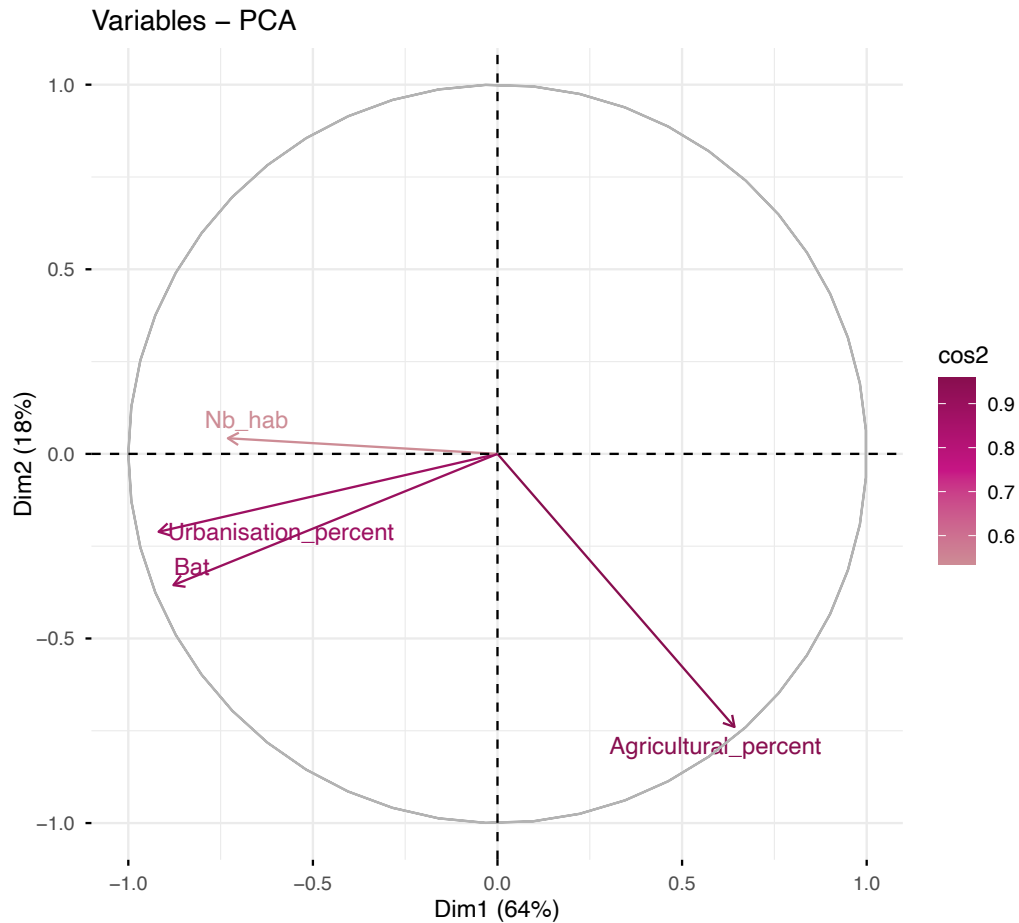
Variable	Use	Definition	Unit / Scale	Data Source	Access
Urban land cover (%)	PCA	Percentage of land classified as artificial surfaces (urban fabric, industrial/commercial units, transport infrastructure)	% within 250 m buffer	CORINE Land Cover 2018 (CLC 2018)	Copernicus Land Monitoring Service, https://land.copernicus.eu
Agricultural land cover (%)	PCA	Percentage of land classified as agricultural areas (arable land, permanent crops, pastures, heterogeneous agricultural areas)	% within 250 m buffer	CORINE Land Cover 2018 (CLC 2018)	Copernicus Land Monitoring Service, https://land.copernicus.eu
No. Inhabitants (Nb_hab)	PCA	Total population of the municipality in which the territory is located	Count	French national census (populations légales 2020)	INSEE, https://www.insee.fr
Building surface (Bat)	PCA	Total footprint surface of buildings	m ² within 250 m buffer	BD TOPO® (national topographic database)	IGN, https://geoservices.ign.fr
Forest land cover (%)	Fixed effects in linear models	Percentage of land classified as forest (broad-leaved, coniferous and mixed forest classes)	% within 250 m buffer	CORINE Land Cover 2018 (CLC 2018)	Copernicus Land Monitoring Service, https://land.copernicus.eu
Altitude	Fixed effects in linear models	Point elevation at the territory's nesting site	m above sea level	BD ALTI® (digital elevation model)	IGN, https://geoservices.ign.fr/bdalti
Global Human footprint index (HFI)	External validation benchmark	Composite index of cumulative human pressure (built environments, population density, land use, roads, railways, navigable waterways)	0–100 (dimensionless), 1 km resolution	Global Human Footprint (Venter et al., 2016a, 2016b)	Wildlife Conservation Society / SEDAC, https://sedac.ciesin.columbia.edu/data/set/wildareas-v3-2009-human-footprint

Supplementary Table S3. Eigenvalues, percentage of variance explained, and cumulative variance explained for the four principal components from the territory-level landscape PCA (urban cover, agricultural cover, and building surface within 250 m of each territory, and number of inhabitants in the municipality). Only PC1 was used as the composite human footprint index ($HFI_{\text{territory}}$) in the primary mixed-effects model; PC2 was tested in a comparison model (Supplementary Table S8).

Principal component	Eigenvalue	Variance explained (%)	Cumulative variance explained (%)
PC1	2.559	63.97	63.97
PC2	0.720	17.995	81.97
PC3	0.589	14.733	96.70
PC4	0.132	3.300	100.00

Supplementary Table S4. Loadings (variable–component correlations) of territory-level landscape variables on the first three principal components from the PCA, and their combined $\cos^2$ (proportion of variance represented) on PC1–PC2. Variables include percent urban land cover, percent agricultural land cover, and building surface within 250 m of each territory, and number of inhabitants in the municipality in which each territory is located. PC1 was defined as a composite human footprint gradient: higher PC1 scores indicate more urbanised territories with more buildings, roads, and inhabitants.

Variable	PC1 loading	PC2 loading	PC3 loading	$\cos^2$ (PC1+PC2)
Urban land cover (%)	0.918	0.211	0.204	0.887
Agricultural land (%)	−0.642	0.740	−0.198	0.960
No. Inhabitants	0.730	−0.042	−0.682	0.535
Building surface	0.878	0.355	0.209	0.897



Supplementary Fig. S2 Correlation circle plot for the first two principal components from the landscape PCA. Arrows represent original landscape variables: percent urban land cover, percent agricultural land cover, and total building surface (Bat) within 250 m of each territory, and number of inhabitants in the municipality (Nb_hab). Variables associated with more urbanised territories (building surface and urban cover) load strongly on PC1; number of inhabitants shows the lowest cos2 (colour scale), indicating it is less well represented in the PC1–PC2 plane than the other variables.

Supplementary methods: Linear mixed models of mercury exposure

In addition to the primary model reported in the main text (forest cover, altitude, and HFIterritory as fixed effects; individual identity and year as random intercepts; Table 2), we fitted four alternative models to test of the robustness of our results, described below.

Raw compositional land-cover model

To justify using the PCA-derived HFIterritory rather than the raw, individual land-cover percentages, we fitted a model with percent urban, agricultural, and forest land cover (all at 250 m) and altitude as fixed effects, using the same random-effects structure as the primary model (individual and year) to allow direct comparison of fixed-effect estimates. Because these three land-cover variables are compositional (summing to 100%), this model showed severe multicollinearity.

Supplementary Table S5. Linear mixed-effects model of log-transformed feather mercury concentrations using raw, individually entered urban, agricultural, and forest land-cover percentages (250 m buffer) and altitude as fixed effects, with the random-effects structure (individual and year). Variance inflation factors (VIF) for each fixed effect are given in the final column; VIFs > 5 indicate problematic collinearity.

Fixed effect	Estimate	95% CI	p value	VIF
Intercept	0.301	[0.213, 0.390]	<0.001	—
Forest land cover (%)	0.014	[−0.164, 0.192]	0.877	18.71
Altitude (m)	−0.161	[−0.209, −0.112]	<0.001	1.24
Urbanisation (%)	−0.080	[−0.237, 0.076]	0.315	16.97
Agricultural land cover (%)	0.047	[−0.141, 0.234]	0.627	22.49
Random effects	Variance			
Individual	0.199			
Year	0.013			
Residual	0.055			
R^2_c / R^2_m	0.819 / 0.117			

Full hierarchical random-effects structure (comparison model)

To evaluate whether retaining river and territory as random effects masked the influence of fixed landscape covariates (see main text), we re-fitted the primary model (forest cover, altitude, HFIterritory) with the full hierarchical random-effects structure (individual, territory nested within river, river, and year) instead of the simplified structure (individual and year only) used in the primary model.

Supplementary Table S6. Linear mixed-effects model of log-transformed feather mercury concentrations with the full hierarchical random-effects structure (river, territory nested within river, individual identity, and year). Marginal and conditional R² values are reported. Variance inflation factors (VIF) for each fixed effect are given in the final column; VIFs > 5 indicate problematic collinearity.

Fixed effect	Estimate	95% CI	p value	VIF
Intercept	0.259	[0.084, 0.433]	0.013	—
Forest land cover (%)	0.008	[−0.043, 0.059]	0.757	1.10
Altitude (m)	−0.035	[−0.109, 0.040]	0.365	1.15
HFIterritory (PC1)	−0.100	[−0.150, −0.051]	<0.001	1.07
Random effects	Variance			
Individual	0.130			
Year	0.010			
Territory	0.026			
River	0.064			
Residual	0.048			
R ² _c / R ² _m	0.833 / 0.035			

Urbanisation model (robustness check using raw urbanisation percent)

To confirm that the human footprint effect captured by the PCA-derived $HFI_{territory}$ was not an artefact of the composite index's construction, we re-fitted the primary model with $HFI_{territory}$ (PC1) replaced by the raw, standardised percentage of urban land cover (250 m buffer) as a single fixed effect, retaining forest cover and altitude and the primary model's random-effects structure (individual and year). This model yielded fixed-effect estimates, confidence intervals, and variance explained that closely matched the primary $HFI_{territory}$ model, and showed no problematic collinearity among fixed effects. We nonetheless retain the PCA-derived $HFI_{territory}$ as our primary measure of human impact, since it integrates several correlated landscape variables (urban cover, agricultural cover, building surface, number of inhabitants) in a single composite index, consistent with standard Human Footprint Index constructions in the literature (Venter et al., 2016a, 2016b).

Supplementary Table S7. Linear mixed-effects model of log-transformed feather mercury concentrations using the raw urbanisation percentage (250 m buffer) in place of $HFI_{territory}$ (PC1), alongside forest cover and altitude as fixed effects, with the primary model's random-effects structure (individual and year). Variance inflation factors (VIF) for each fixed effect are given in the final column; VIFs > 5 indicate problematic collinearity.

Fixed effect	Estimate	95% CI	p value	VIF
Intercept	0.302	[0.212, 0.391]	<0.001	—
Forest land cover (%)	-0.028	[-0.077, 0.020]	0.254	1.23
Altitude (m)	-0.164	[-0.211, -0.117]	<0.001	1.12
Urbanisation (%)	-0.118	[-0.163, -0.073]	<0.001	1.17
Random effects	Variance			
Individual	0.199			
Year	0.013			
Residual	0.055			
R^2_c / R^2_m	0.819 / 0.117			

Model including the second principal component (PC2)

To confirm that the human footprint effect (PC1) was not sensitive to the exclusion of PC2 (the agricultural axis) from the primary model, we fitted a model including both PC1 and PC2 alongside forest cover and altitude, using the same random-effects structure as the primary model (individual and year) to allow direct comparison of fixed-effect estimates. Forest cover and PC2 were strongly correlated in this model, resulting in elevated variance inflation factors for both.

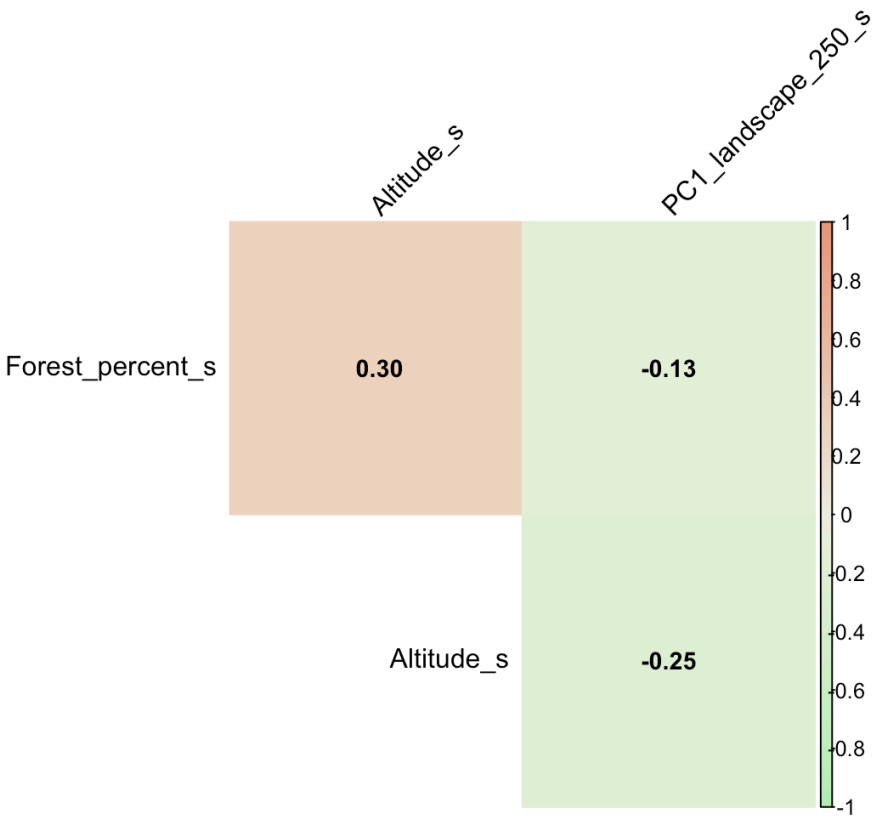
Supplementary Table S8. Linear mixed-effects model of log-transformed feather mercury concentrations including both PC1 (HFIterritory) and PC2 (agricultural axis) from the landscape PCA, alongside forest cover and altitude (N = 745 observations). PC1 retains a significant negative association with mercury consistent with the single-PC1 model; PC2 shows no independent association. Random effects, marginal and conditional R^2 values are reported. Variance inflation factors (VIF) for each fixed effect are given in the final column; VIFs > 5 indicate problematic collinearity.

Fixed effect	Estimate	95% CI	p value	VIF
Intercept	0.303	[0.215, 0.391]	<0.001	—
Forest land cover (%)	−0.067	[−0.196, 0.062]	0.308	9.06
Altitude (m)	−0.176	[−0.226, −0.127]	<0.001	1.26
PC1 (HFIterritory)	−0.129	[−0.174, −0.084]	<0.001	1.20
PC2 (agricultural axis)	−0.088	[−0.216, 0.040]	0.179	9.41
Random effects	Variance			
Individual	0.196			
Year	0.012			
Residual	0.052			
R^2_c / R^2_m	0.822 / 0.116			

Supplementary methods: Collinearity for the in-text mixed effect model

Supplementary Table S9. Variance inflation factors (VIFs) for standardized fixed-effect predictors used in the primary mixed-effects model of log-transformed feather mercury concentrations (Table 2, main text). All VIFs were low (< 1.15), indicating no problematic collinearity among fixed effects.

Predictor	VIF
Forest land cover	1.10
Altitude	1.15
Human Impact PC1	1.07



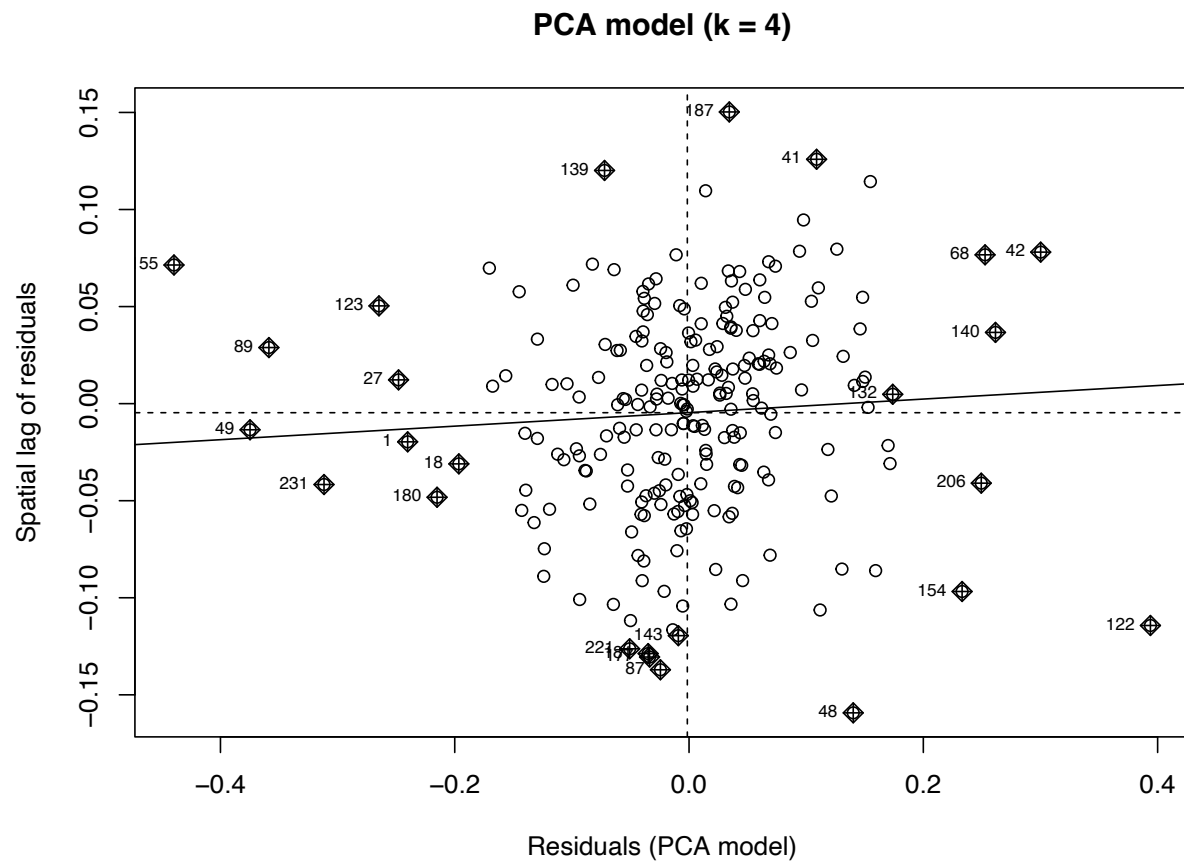
Supplementary Fig. S3 Correlation heatmap showing pairwise Pearson correlation coefficients among standardized fixed-effect predictors (forest land cover, altitude, and human footprint index PC1) used in the primary mixed-effects model of log-transformed feather mercury concentrations. All correlations were modest ($|r| \leq 0.30$), indicating no problematic collinearity among fixed effects.

Supplementary methods: Spatial autocorrelation diagnostics

To confirm that our primary results were not sensitive to the choice of $k = 4$ nearest neighbours, we repeated the Moran's I test on site-averaged residuals from the primary model (individual identity and year as random intercepts) using $k = 3, 5$, and 6 nearest neighbours. Moran's I remained non-significant across all values tested, consistent with the $k = 4$ result reported in the main text.

Supplementary Table S10. Sensitivity of Moran's I to the choice of k (number of nearest neighbours) in the spatial weights matrix, calculated on site-averaged residuals from the primary mixed-effects model (individual identity and year random effects only). The $k = 4$ result (bold) is reported as the primary test in the main text; $k = 3, 5$, and 6 are reported as a sensitivity analysis. An additional $k = 8$ test was run but excluded from the final sensitivity range because larger neighbourhoods began linking territories across different rivers, weakening the ecological interpretation of 'spatial neighbour' in this system.

k	Moran's I	Expected I	z	p value
3	0.023	−0.004	0.55	0.581
4 (primary)	0.033	−0.004	0.88	0.381
5	0.027	−0.004	0.81	0.418
6	0.045	−0.004	1.41	0.159



Supplementary Fig. S4 Moran scatterplot of site-averaged residuals from the primary mixed-effects model of log-transformed feather mercury concentrations (individual identity and year random effects only). Residuals were averaged at the territory level and Moran's I was calculated using k-nearest-neighbour (k = 4) spatial weights based on territory site coordinates.

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