Table S1. Description and data sources of environmental variables used in GeoDetector analysis.

Category	Variable	Abbr.	Description	Data source
Human activity and land cover	Nighttime light	NTL	Proxy for regional human activity intensity and urban-industrial disturbance	VIIRS Nighttime Lights Version 1, Earth Observation Group, NOAA National Centers for Environmental Information (https://ngdc.noaa.gov/eog/viirs/download_dnb_composites.html ; accessed in March 2025).
	Euclidean distance to factories	ED_Fac	Distance to industrial facilities, representing proximity to potential industrial emission sources	Industrial facility data compiled for this study; Euclidean distance was derived in ArcGIS Pro (accessed in March 2025).
	Euclidean distance to mining areas	ED_Min	Distance to mining areas, indicating potential influence of mining-related emissions	Mining-area data compiled for this study; Euclidean distance was derived in ArcGIS Pro (accessed in March 2025).
	Euclidean distance to roads	ED_Road	Distance to road network, reflecting traffic-related inputs and transport corridors	Road network manually interpreted from Sentinel-2 satellite imagery; Euclidean distance was derived in ArcGIS Pro (accessed in March 2025)
	Euclidean distance to cropland	ED_Crop	Distance to cropland, representing the potential influence of agricultural activities	Cropland polygons manually interpreted from Sentinel-2 satellite imagery; Euclidean distance was derived in ArcGIS Pro (accessed in March 2025).
	PM10 concentration	PM10	Proxy for atmospheric deposition intensity and airborne particulate input	The data are provided by the China Meteorological Administration (http://www.cma.gov.cn/) for the period of 2024.1.1 to 2025.1.1.
	Land use/land cover	LULC	Land surface use pattern, reflecting differences in anthropogenic disturbance and surface cover	Land use/land cover data manually interpreted from Sentinel-2 satellite imagery (accessed in March 2025).
Natural environment	Elevation	DEM	Topographic elevation controlling terrain pattern and pollutant redistribution	SRTM DEM data with a resolution of 30 m (https://www.earthdata.nasa.gov/)
	Slope	Slope	Local terrain steepness affecting runoff, erosion, and material transport	Derived from the digital elevation model used in this study through terrain analysis in ArcGIS Pro (accessed in March 2025).
	Height above nearest drainage	HAND	Relative drainage position describing local hydrological connectivity and potential flow convergence	Derived from the digital elevation model and drainage network through hydrological terrain analysis in ArcGIS Pro (accessed in March 2025).
	Average precipitation	Pre_avg	Mean of the 12 monthly precipitation totals in 2023, representing average monthly precipitation conditions.	Monthly precipitation data from meteorological data assimilation products provided by the China Meteorological Data Service Centre (https://data.cma.cn/), covering January–December 2023. Pixel-wise temporal aggregation was used to calculate the mean and maximum monthly precipitation.
	Maximum	Pre_max	Maximum of the 12	Monthly precipitation data from

	precipitation		monthly precipitation totals in 2023, representing the wettest month at each location.	meteorological data assimilation products provided by the China Meteorological Data Service Centre (https://data.cma.cn/), covering January–December 2023. Pixel-wise temporal aggregation was used to calculate the mean and maximum monthly precipitation.
	Normalized difference vegetation index	NDVI	Vegetation cover indicator reflecting ecological condition and surface retention capacity	MODIS Vegetation Indices (MOD13Q1) Product. NASA LP DAAC. Available at: https://lpdaac.usgs.gov/ (accessed on March, 2025).
Geological and soil background	Parent material	PM	Soil-forming parent material representing geogenic background and lithological control	Digitized from the parent-material distribution map in Appendix A of DB 4402/T 08–2021.
	Soil organic carbon	SOC	Soil adsorption and retention capacity for heavy metals	The data obtained from the National Soil Chemical Survey Project of China Geological Survey.

Table S2. Parent-material-specific geochemical background values for soil heavy metals in the study area (mg kg−1).

Parent material type	Cr	Zn	Pb	Cd	As	Hg
Carbonate rock	123.90	290.00	200.80	1.85	158.20	0.43
Quaternary sediment	105.40	153.40	113.20	1.10	55.84	0.36
Sandstone and shale	112.00	143.40	125.80	1.15	82.34	0.29
Purplish-red sandstone and shale	75.11	112.40	86.32	0.62	24.23	0.22
Metamorphic and epimetamorphic rock	106.00	136.95	107.95	0.61	98.14	0.24
Acidic volcanic extrusive rock	237.70	140.20	131.10	0.69	204.60	0.18
Granitic	48.28	107.80	115.00	0.38	21.08	0.21

* Background values correspond to the 95th percentiles reported in DB 4402/T 08–2021. Shaoguan Municipal Administration for Market Regulation. DB4402/T 08–2021: Environmental Background Values of Soil; Shaoguan Municipal Administration for Market Regulation: Shaoguan, China, 2021.

Table S3. Source attribution of stable high–high clusters of total ecological risk.

Site	Total RI	Risk class	Dominant source	Dominant-source share	Dominant risk element
1B	283.74	Moderate	F2	73.32%	Cd
3B	330.94	High	F2	93.32%	Cd
5B	1898.95	Very high	F2	98.71%	Cd
6B	292.97	Moderate	F2	88.54%	Cd
9B	355.78	High	F2	90.38%	Cd
HC241698010001	340.02	High	F2	85.65%	Cd
N0303-028	96.40	Low	F3	47.96%	Hg
N0303-099	246.88	Moderate	F2	90.02%	Cd
N0303-100	129.11	Low	F2	81.26%	Cd
N0303-144	275.12	Moderate	F2	90.76%	Cd
N0303-145	1356.55	Very high	F2	92.49%	Cd
N0303-146	69.98	Low	F2	80.05%	Cd

* Stable HH denotes statistically significant local high–high spatial association based on log-transformed total RI values, with FDR correction and neighborhood-sensitivity criteria. It is distinct from the absolute ecological risk classification based on total RI thresholds.

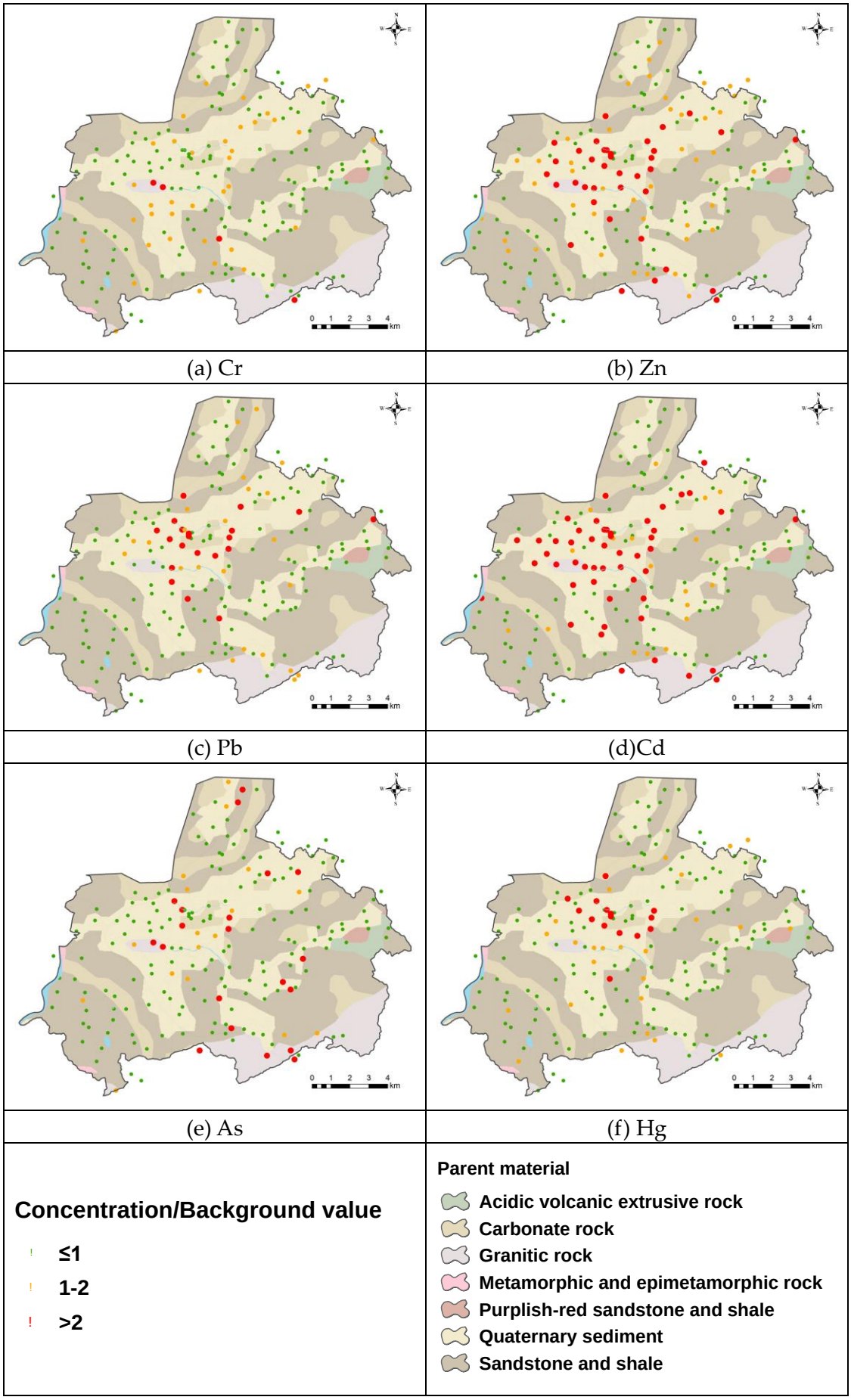


Figure S1. Spatial enrichment of Cr, Zn, Pb, Cd, As, and Hg relative to parent-material-specific background values. Green, orange, and red symbols represent C/B ≤ 1, 1 < C/B ≤ 2, and C/B > 2, respectively. The background polygons represent different parent-material types.

Table S4. Sensitivity of ecological risk assessment to the selection of parent-material-specific background values.

Indicator	95th percentile	Median
Mean RI	119.35	547.34
Low-risk sites	158	56
Moderate-risk sites	17	64
High-risk sites	11	33
Very-high-risk sites	5	38
F2 risk contribution (%)	74.50	80.94
F2-dominated high-/very-high-risk sites	16/16	66/71

* The same RI classification thresholds were applied to both scenarios. PMF source allocations and toxic-response coefficients were held constant.

Table S5. Resampling-based uncertainty and ranking stability of source-specific ecological risk contributions.

Resampling procedure	Valid replicates	Median (%)	2.5th–97.5th percentile (%)	F2 largest
Fixed PMF, site bootstrap	1000	74.23	67.82–80.01	1000/1000
PMF refitting, original-site projection	199	74.62	71.81–76.78	199/199
Joint bootstrap and refitting	199	74.40	67.91–80.55	199/199
Spatial block, 3 km	1000	73.97	60.91–81.54	1000/1000
Spatial block, 5 km	1000	74.20	58.72–81.00	1000/1000
Spatial block, 7 km	1000	74.33	56.43–80.13	999/1000