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Research Article

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Persistence of cross-media toxic release profiles across U.S. counties

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Abstract

Reported toxic releases are commonly summarized by total mass, although changes in the receiving medium and local industrial composition can alter the interpretation of a county trend. This study evaluates the persistence of county profiles of reported air, water, and land releases using U.S. Environmental Protection Agency Toxics Release Inventory Basic Plus files for 2015–2022. Releases were converted to pounds, assigned to media, and aggregated by county, year, and 31 industry sectors. Early- and late-period three-medium profiles were compared using cosine similarity. Two sensitivity analyses recalculated similarity after giving represented sectors equal weight and after removing the county’s largest early-period sector. The data contained 84,260 county-year-sector records from 2,594 counties; 2,463 counties supported the two-window stability analysis. Nationally, land received 49.4–60.8% of reported mass across study years, air 29.9–37.8%, and water 9.3–13.1%. Median raw profile similarity was 0.983. The median was 0.973 after sector equalization and 0.919 after the largest sector was removed. High raw persistence therefore coexisted with meaningful dependence on the dominant local sector. TRI mass is not toxicity weighted and does not measure ambient concentration or human exposure. Cross-media release profiles should be reported with industry-composition sensitivity and separate medium-specific quantities rather than interpreted as county environmental risk scores.

Keywords: Toxics Release Inventory; pollutant release and transfer register; compositional data; industrial structure; county monitoring; sensitivity analysis

1 Introduction

Pollutant release and transfer registers use mandatory disclosure to make industrial environmental information available to regulators, communities, investors, and researchers. The U.S. Toxics Release Inventory (TRI) is a prominent example and has supported studies of environmental performance, information disclosure, environmental justice, and geographic patterns of reported releases [1–12]. Similar registers have been developed in Japan, Europe, and other jurisdictions [13–16].

TRI records are often aggregated to a total mass for a facility, industry, or county. A total is useful, but it does not show whether releases were reported to air, surface water, or land. The media profile matters because the routes, management practices, and interpretation differ. At the same time, a county profile can be dominated by one industry sector or a small number of facilities. Apparent temporal stability may therefore reflect a stable industrial mix rather than similar patterns within sectors.

Existing TRI research has linked reported releases to health or demographic outcomes and developed risk-weighted approaches [17–23]. Such work requires careful exposure and toxicity assumptions. The

present study takes a prior measurement step. It asks how persistent the reported cross-media composition is and how that persistence changes when industry-sector weights are altered. No health outcome is analyzed, and no release is converted into ambient concentration, exposure, or toxicity-weighted harm.

The study addresses three questions. How did the national shares of air, water, and land releases vary from 2015 to 2022? How similar were county profiles between early and late windows? How much did similarity change under sector-equalization and removal of the largest sector? The contribution is a reproducible composition-sensitivity audit for county TRI summaries.

2 Data and methods

2.1 TRI records and media classification

TRI Basic Plus files for 2015–2022 were obtained from the EPA public archive [24, 25]. Facility coordinates and county identifiers were taken as reported. Records lacking a valid county code or necessary release quantity were excluded from the relevant aggregation. Industry was represented by the sector classification available in the files, yielding 31 sectors in the harmonized analysis.

Reported quantities were converted to pounds using the units supplied in each file. Air releases combined fugitive and stack air quantities. Surface-water discharges formed the water category. On-site land disposal and other land releases formed the land category. Quantities outside these three on-site media were not reassigned. The analysis follows EPA cautions that TRI values are reported quantities and should not be treated as direct measures of risk [26].

2.2 County profiles

Let M_{cktp} denote reported mass for county c , industry sector k , year t , and medium $p \in \{A, W, L\}$. Annual national shares were calculated after summing over counties and sectors. For county-window comparisons, years were grouped into early and late periods of equal length. The raw county profile was

$$q_{cp}^{(h)} = \frac{\sum_{k,t \in h} M_{cktp}}{\sum_{p'} \sum_{k,t \in h} M_{cktp'}}, \quad (1)$$

where h denotes the time window. Counties required positive total mass in both windows.

Figure 1 separates the reporting fields, profile-construction step, three comparative estimands, and evidence synthesis. The parallel analytical lenses distinguish observed-mass composition from sector-balanced composition and dominant-sector perturbation, while the lower boundary records what the design cannot infer. This architecture prevents a high reported mass from being interpreted as a toxicity or exposure score and makes each sensitivity operation traceable.

2.3 Persistence and composition sensitivity

Raw persistence was the cosine similarity between early and late three-medium profiles. With nonnegative components, similarity ranges from zero to one, and one indicates identical proportional allocation across media. The metric evaluates composition, not the scale of total releases. Early and late totals were therefore retained as separate quantities.

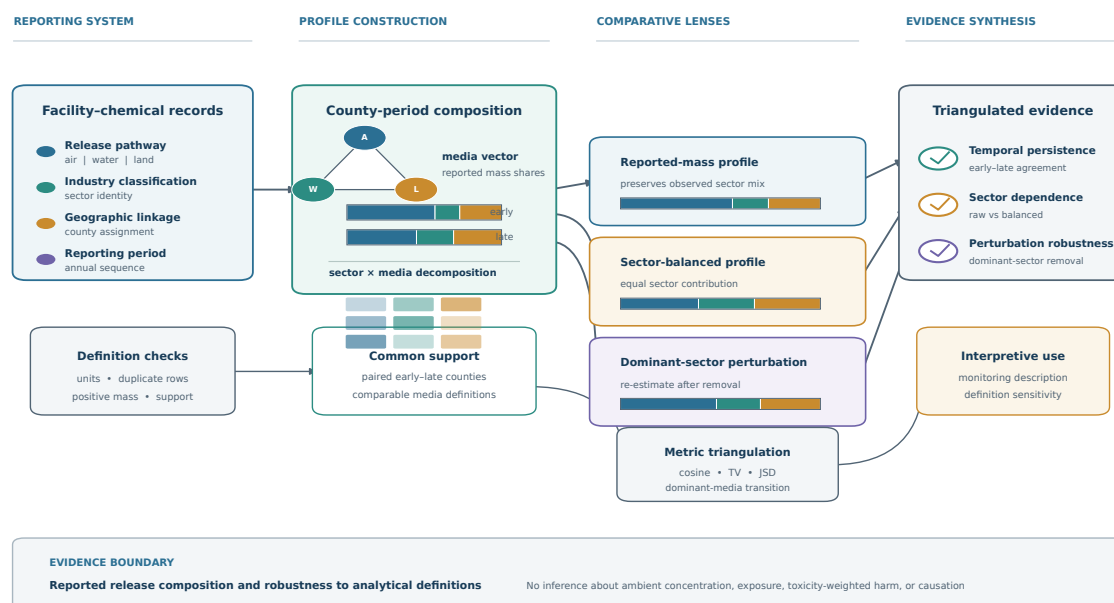


Figure 1: Cross-media compositional analysis architecture. TRI reporting fields are harmonized into paired county-period media profiles, evaluated using reported-mass, sector-balanced, and dominant-sector perturbation lenses, and synthesized through complementary similarity metrics. The framework describes reported release composition only; it does not estimate ambient concentration, exposure, toxicity-weighted harm, or causal effects.

Two sensitivity profiles were calculated. In the sector-equalized profile, each represented industry sector contributed equal weight after its within-sector media shares were computed. This prevents a high-mass sector from automatically controlling the county composition. In the second analysis, the sector with the largest early-period total was removed from both windows before profiles were recomputed. The deletion is a stress test, not a claim that the sector will leave the county.

For each metric, the distribution across counties was summarized by the mean, standard deviation, quartiles, minimum, and maximum. The deterministic processing script fixed conversions, classifications, and period definitions before computing the outputs.

3 Results

3.1 National cross-media composition

The harmonized data contained 84,260 county-year-sector records across 2,594 counties and 31 industry sectors. National reported mass ranged from 1.532 billion pounds in 2020 to 2.072 billion pounds in 2017 (Table 1). Land was the largest medium every year, with a share from 0.494 in 2021 to 0.608 in 2017. Air shares ranged from 0.299 to 0.378, and water shares from 0.093 to 0.131.

The national series shows why the media composition should accompany totals. The highest total year, 2017, also had the largest land share and smallest air and water shares. A change in total mass therefore did not imply a proportional change in every medium.

Table 1: National on-site reported release mass and media shares.

Year	Total (billion lb)	Air share	Water share	Land share
2015	1.846	0.378	0.108	0.514
2016	1.713	0.362	0.114	0.524
2017	2.072	0.299	0.093	0.608
2018	1.828	0.342	0.108	0.550
2019	1.714	0.353	0.119	0.528
2020	1.532	0.362	0.129	0.509
2021	1.535	0.375	0.131	0.494
2022	1.589	0.338	0.110	0.551

3.2 County profile stability

The two-window analysis included 2,463 counties. Median raw-profile similarity was 0.983, with an interquartile range of 0.916–1.000. The mean was lower, 0.908, and the minimum was close to zero, indicating a minority of counties with large compositional change.

After equalizing represented industry sectors, 2,326 counties had defined profiles. Median similarity was 0.973, the interquartile range was 0.879–1.000, and the mean was 0.909. Although the medians were close, the lower first quartile under equalization indicates that the raw mass-weighted profile concealed change for some counties.

The strongest sensitivity arose after removing the largest early-period sector. Median similarity fell to 0.919. This remains high in absolute terms, but the decline from 0.983 shows that dominant-sector continuity accounted for a meaningful portion of the apparent persistence.

Table 2 summarizes the county counts and distributional statistics for the raw, sector-equalized, and dominant-sector-removal specifications.

Table 2: County profile-stability summaries under alternative industry weighting.

Metric	Counties	Mean	Q1	Median	Q3
Raw similarity	2,463	0.908	0.916	0.983	1.000
Sector-equalized similarity	2,326	0.909	0.879	0.973	1.000
Top-sector-removed similarity	2,463	–	–	0.919	–

Early-period county total mass was highly skewed: the median was 184,031 lb, the first quartile 17,463 lb, and the maximum exceeded 2.03 billion lb. Late-period totals had a median of 162,872 lb and a maximum of 1.30 billion lb. This scale heterogeneity reinforces the need to distinguish a proportional profile from the quantity on which it is based.

Figure 2 presents the national media shares together with the county-level temporal-persistence diagnostics used to compare the three specifications.

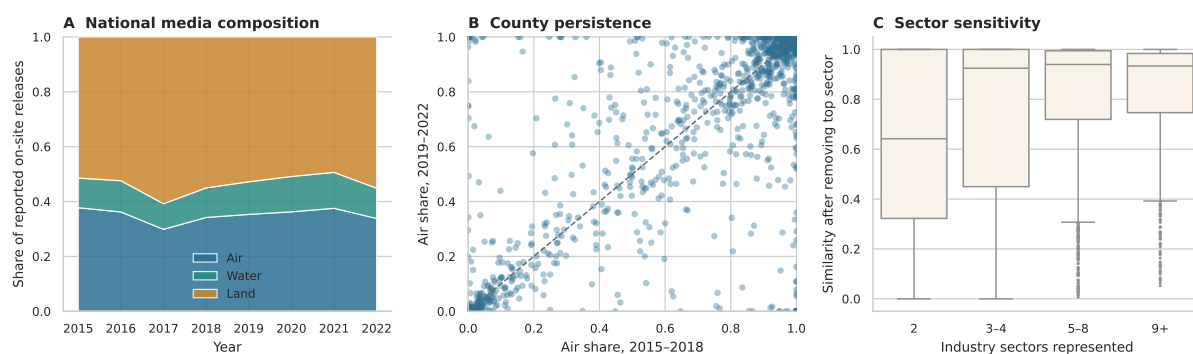


Figure 2: National cross-media shares and county temporal-persistence diagnostics under raw, sector-equalized, and dominant-sector-removal specifications. Values are unweighted reported mass.

4 Discussion

4.1 Persistence and its industrial basis

County cross-media profiles were highly persistent under the raw mass-weighted specification. This means that the proportional allocation of reported mass among air, water, and land often changed little between windows. It does not mean that total releases were unchanged, that facilities complied with regulation, or that environmental conditions were stable.

The sector sensitivity results qualify the raw persistence. Equalization produced a modest reduction in the median but a larger change in the lower quartile. Removing the dominant early-period sector reduced the median to 0.919. In many counties, the leading sector therefore anchors the cross-media profile. This is not a statistical defect: the dominant sector is part of the real reported industrial structure. It is nevertheless important when a profile is used to describe the county rather than the sector.

A practical reporting approach would present three related objects: total reported mass by medium, the raw media profile, and a composition-sensitivity interval or alternative profile. The raw result answers what was reported from the observed facility mix. Sector equalization answers how the profile changes when represented sectors contribute equally. Dominant-sector removal shows whether the conclusion survives a severe composition perturbation. None should be designated as the uniquely correct county profile without a decision-specific rationale.

4.2 Relation to right-to-know research

TRI research has shown that information disclosure can influence public attention and firm behavior [4, 8–12]. The value of disclosure depends partly on whether summaries preserve the structure of the underlying reports. A single cross-media total may be easy to communicate but can hide shifts among air, water, and land. A toxicity-weighted score adds substantive assumptions and data requirements. The present composition audit occupies an intermediate position: it remains close to reported quantities while making the medium and industry dimensions visible.

The framework also applies to other pollutant release and transfer registers. Cross-jurisdiction comparison would require harmonized media definitions, units, industry codes, thresholds, and reporting rules. Differences in those institutional features may dominate apparent environmental differences. The current U.S.-only design avoids that additional layer but cannot establish international generalizability.

4.3 Limitations

TRI includes facilities and chemicals meeting statutory reporting criteria. It omits nonreporting facilities, diffuse sources, and releases below applicable thresholds. Reported mass can be revised and is not equivalent to environmental concentration, dose, toxicity, or damage [26]. The study does not distinguish chemicals by potency and should not be used to rank health risk.

Media categories combine heterogeneous practices. “Land” includes several on-site disposal pathways, and “air” combines fugitive and stack releases. More detailed submedia profiles could identify different patterns but would increase sparsity. Transfers off site and waste-management quantities were not folded into the three on-site media because doing so would change the meaning of the profile.

Industry equalization gives the same weight to every represented sector regardless of facility count or output. It is a sensitivity design, not an economic or environmental weighting scheme. Removing the largest sector is deliberately severe and may leave a profile based on little mass. Cosine similarity can be high when both profiles are dominated by one medium, even if total mass changes sharply. Finally, county aggregation can obscure localized conditions and creates no basis for individual exposure inference.

5 Additional analyses and robustness assessment

5.1 Release accounting and compositional construction

The analytical unit before aggregation is a county-year-industry-sector record containing reported on-site air, water, and land releases. The processed file included 84,260 such records, covering 2,594 counties, 31 sectors, and eight reporting years. This structure retains the industry layer needed for sensitivity analysis. Aggregating immediately to county totals would reproduce a conventional public summary but would make it impossible to distinguish media stability from stability in the represented sector mix.

Reported pounds were kept in their source accounting units and assigned to three broad on-site media. The composition for a county-period was obtained by dividing each medium by the sum across media. The resulting shares sum to one and describe allocation, not toxicity or exposure. Counties with zero total in a comparison period require explicit treatment because a composition is undefined. The stability analysis retained 2,463 counties with the support needed for the declared comparisons.

Cosine similarity was used because it summarizes directional agreement among nonnegative media shares and remains interpretable near the simplex boundaries. A value near one indicates that the relative allocation across media was similar in the two periods. It does not indicate that total release mass was similar. The analysis therefore retains early and late totals alongside similarity, rather than converting composition into a comprehensive performance score.

5.2 National context and county heterogeneity

National on-site total reported mass changed from 1.846 billion pounds in 2015 to 1.589 billion pounds in 2022, with an intervening maximum of 2.072 billion pounds in 2017. The media allocation also varied. Land accounted for 51.44% in 2015, rose to 60.81% in 2017, and was 55.14% in 2022. Air declined from 37.75% to 33.84% between 2015 and 2022, while water remained much smaller, ranging from 9.33% to 13.09% across the series.

These national values provide scale but not a representative county trajectory. County totals were highly skewed: the median early-period total was 184,031 pounds and the upper quartile was about 1.025 million, while the maximum exceeded 2.032 billion. In the later period, the median was 162,872 pounds, the upper quartile about 898,885, and the maximum about 1.298 billion. A small number of large reporters can dominate aggregate mass even though most counties occupy a very different scale range.

The raw county media profiles were nevertheless highly persistent. Median similarity was 0.983 and the first quartile was 0.916; the mean was lower at 0.908 because a minority of counties had very low similarity. Air dominated many county compositions: median air shares were 0.996 in the early period and 0.997 in the later period. Boundary-heavy compositions help explain why cosine similarity can be near one even when totals change materially.

5.3 Industry-composition sensitivity

Sector equalization asks what the county profile would look like if each represented sector contributed equal weight to the media composition. This is not an estimate of economic output or an environmental optimum. It deliberately removes the direct mass dominance of large sectors so that within-sector media allocation contributes more evenly. Among 2,326 counties with a defined equalized comparison, median similarity was 0.973 and the first quartile was 0.879.

Removing the largest sector is a more severe perturbation. Median similarity after that removal was 0.919, lower than both the raw and equalized medians. The decline indicates that dominant sectors contribute to apparent persistence for a meaningful subset of counties. It does not mean that the raw profile is wrong. The raw, equalized, and leave-dominant-sector results describe three different weighting schemes and should be interpreted together.

The differing denominators also matter. Raw similarity was available for 2,463 counties, whereas sector equalization was defined for 2,326. Counties with only one represented sector cannot contribute the same kind of within-county sector comparison. Excluding them silently would make the equalized result appear universally applicable. The manuscript therefore reports support counts with every stability summary.

5.4 Robustness and decision use

Alternative metrics could emphasize different changes. Aitchison distance would use log-ratios but requires a principled zero-replacement rule. Total-variation distance is directly interpretable as share reallocation but treats all media symmetrically. Jensen–Shannon divergence offers a bounded information measure. Cosine similarity was selected for a transparent first audit; future applications should compare metrics when decisions depend on a particular distance threshold.

Chemical-specific or toxicity-weighted analyses would answer substantively different questions. They require fate, potency, and exposure information and would change the interpretation from reported mass allocation toward potential hazard. Similarly, including off-site transfers would expand the system boundary from on-site releases to waste movement and management. Those extensions are valuable, but combining them without a declared accounting boundary would obscure what the published profile represents.

A reproducible county release report should therefore include total reported mass, the three media

shares, the sectors represented, and at least one composition-sensitivity result. The archive preserves the source-year files, county-year-sector table, raw and equalized period profiles, and leave-top-sector-out results. Together they allow every summary to be traced to reported TRI quantities while preventing the profile from being interpreted as ambient concentration, dose, health risk, or unreported pollution.

5.5 Quality controls and external validation

Processing checks verified nonnegative media quantities, valid reporting years, consistent county identifiers, recognized industry sectors, and agreement between sector-level and county-level totals. Period profiles were only calculated after reconciling these sums. Similarity metrics were checked against their theoretical bounds, and denominator counts were retained for raw, equalized, and sector-removal analyses. These controls address transformation errors but do not independently audit facility submissions.

An external validation could examine counties with the largest decline from raw to sector-equalized similarity. Facility-level histories, chemical composition, and documented openings or closures would help distinguish real industrial restructuring from reporting changes. A second validation could compare TRI media profiles with state pollutant-release summaries where accounting boundaries align. Such work would deepen interpretation but would not justify replacing the present mass-based evidence with concentration or risk claims.

The study therefore provides an auditable descriptive layer. It identifies when a stable public summary is conditional on industrial composition and supplies the data objects needed for targeted follow-up. This role is narrower than environmental risk assessment but directly relevant to transparent use of pollutant release registers.

Reuse should preserve the same on-site media boundary or state any expansion explicitly. Mixing off-site transfers, treatment quantities, and on-site releases in one profile would change both the denominator and the meaning of persistence. The archived sector-level construction makes that boundary testable.

6 Extended compositional and sector-sensitivity analyses

6.1 Triangulating profile persistence

Cosine similarity emphasizes the angle between nonnegative composition vectors. To test whether the high persistence result depended on that geometry, the same early and late media shares were evaluated with total-variation and Jensen–Shannon measures. Their median similarity transformations were 0.9977 and 0.9997, respectively (Table 3). Both confirmed high central persistence, but their lower-tail quantiles differed from cosine similarity because they weight movement near the simplex boundaries differently.

Table 3: Quantiles of early-late persistence under five composition and sector-sensitivity metrics.

Quantile	Cosine: raw	Cosine: sector-equalized	Total-variation similarity	Jensen–Shannon similarity	Leave-top-sector-out similarity
0.050	0.453	0.602	0.500	0.648	0.148
0.250	0.916	0.879	0.952	0.993	0.542
0.500	0.983	0.973	0.998	1.000	0.892
0.750	1.000	1.000	1.000	1.000	0.991
0.950	1.000	1.000	1.000	1.000	1.000

Metric agreement at the median should not be treated as interchangeability. Total variation has a direct share-reallocation interpretation: a distance of 0.10 means that one tenth of the composition would

have to be reallocated to match the other period. Jensen–Shannon divergence emphasizes information change and remains defined with zero shares. Cosine similarity can remain high when one dominant medium is stable and small media shares move. Reporting several prespecified metrics is therefore most useful in the lower tail, where counties depart from the near-one cluster.

6.2 Release scale and persistence

The county distribution was divided into quartiles of the geometric mean of early- and late-period reported release mass. Median raw similarity declined from 1.000 in the lowest-mass quartile to 0.959 in the highest, with a total range of 0.959–1.000 (Table 4). This pattern does not mean that large-release counties perform worse. Larger reported totals are often produced by more facilities, sectors, chemicals, and media pathways, which creates more opportunities for composition to change.

Table 4: Profile persistence by quartile of geometric-mean reported release mass across periods.

Mass quartile	Counties	Median geometric-mean pounds	Raw cosine	Equalized cosine	TV similarity	JS similarity	Leave-top-sector-out
Q1 lowest	616	322.876	1.000	1.000	1.000	1.000	0.661
Q2	616	63622.427	0.994	0.988	1.000	1.000	0.959
Q3	615	383782.880	0.980	0.964	0.998	1.000	0.949
Q4 highest	616	2866634.517	0.959	0.956	0.981	0.998	0.802

The mass-stratified table also shows why composition and scale must remain separate. A low-mass county can have a perfectly stable all-air profile, while a high-mass county can reallocate a modest share among media yet still report a large absolute change in pounds. No metric in the table is toxicity weighted, and none estimates concentration or exposure. The quartiles organize the descriptive support of the composition, not environmental harm.

6.3 Sector support and dominance

Industrial diversity was measured by the minimum number of represented sectors in either four-year period. Among the 2,463 counties in the raw comparison, 556 had only one sector in at least one period, 430 had two, 577 had three or four, and 900 had at least five. Median raw similarity declined from 1.000 in the one-sector group to 0.965 in the five-or-more group, while the median largest-sector share declined from 1.000 to 0.711 (Table 5). The overall median largest-sector share was 0.919.

Table 5: Persistence and sector dominance by the minimum number of represented sectors in either period.

Minimum sectors	Counties	Median raw cosine	Median equalized cosine	Median largest-sector share
1	556	1.000	1.000	1.000
2	430	0.989	0.988	0.992
3-4	577	0.983	0.972	0.903
5 or more	900	0.965	0.951	0.711

The pattern identifies a structural reason for apparently perfect persistence. A one-sector county has no within-county sector mixture to change, and a profile concentrated in one sector can remain stable even if the set of facilities changes. More diversified counties provide a stricter test because sector weights and within-sector media allocations can both move. Sector equalization and leave-top-sector-out results should therefore be reported with the number of sectors and the support denominator, not as universal corrections applied identically to all counties.

6.4 Dominant-media transitions

The dominant reported medium remained the same in 94.1% of counties. Air-to-air persistence accounted for the largest cell, but land and water also showed substantial diagonal counts (Table 6). Off-diagonal transitions were uncommon relative to the diagonal, yet they identify counties whose leading reported pathway changed across periods. These cases merit examination of facility and chemical records before any substantive interpretation.

Table 6: Dominant reported release medium in the early and late periods.

Early dominant medium	Late: air	Late: land	Late: water
air	2,039	34	38
land	35	139	4
water	26	8	140

Dominant-medium transitions are intentionally coarse. A county can retain the same leading medium while its minority shares change greatly, or switch leaders when two shares are close. The transition table is therefore paired with continuous metrics. The discrete view identifies a change in the leading pathway; the continuous views quantify the entire composition. Agreement across both forms strengthens a descriptive persistence statement, whereas disagreement reveals a boundary case rather than an error.

6.5 Evidence boundary and reproducible use

The extended results reinforce a narrow conclusion. Reported county media profiles are highly persistent at the center of the national distribution, but apparent stability depends on release scale, sector support, sector weighting, and the selected similarity geometry. These dependencies are visible only because the archived county-year-sector table preserves the industry layer before aggregation.

The analysis remains a reported-mass audit. It does not include toxicity weights, fate and transport, stack or discharge conditions, environmental concentrations, population proximity, dose, or unreported releases. A risk-oriented extension would require those data and a separate model. The present tables instead provide a reproducible basis for choosing counties and records that warrant such follow-up.

7 Conclusions

Reported TRI media profiles were highly persistent across U.S. counties, but part of that persistence depended on the dominant industry sector. National totals also changed alongside the allocation among air, water, and land. County summaries should therefore keep total mass, medium composition, and industry sensitivity separate. This provides a more transparent account of reported releases while respecting the limits of TRI as a disclosure system rather than a direct measure of environmental concentration or human risk.

Data availability

TRI Basic Plus files and reporting documentation are publicly available from the U.S. EPA [24–26]. Derived county-year-sector tables and the deterministic analysis script are included in the accompanying reproducibility files.

Ethics statement

The study used public facility and aggregate release records and involved no human participants or identifiable private information. Institutional ethics review was not required.

Author contributions

Chao Zhang: Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing—original draft, and writing—review and editing.

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Competing interests

The author declares no competing interests.

Declaration of AI-assisted tools

During manuscript preparation, the author used an AI-assisted language tool for drafting support and language editing. The author critically reviewed and revised the manuscript and accepts full responsibility for its content.

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