

Cumulative residential proximity to toxic hazard sites and chronic disease prevalence in the United States: a nationwide ecological cross-sectional study

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Abstract

Background. Residential proximity to toxic hazard sites may contribute to chronic disease burden, but national evidence examining multiple site types and potentially susceptible communities remains limited. To examine associations between residential proximity to toxic hazard sites and chronic disease prevalence across census tracts in the contiguous United States, and variation by social vulnerability and rurality.

Methods. We conducted an ecological, cross-sectional study of 71,638 census tracts in the contiguous United States. Toxic hazard proximity used 2022 Environmental Justice Index rankings for National Priorities List, Toxic Release Inventory, Treatment, Storage, and Disposal, and Risk Management Plan sites. Outcomes were 2020 and 2021 CDC PLACES tract-level prevalence estimates for eight chronic diseases. Population-weighted mixed-effects models estimated prevalence-point differences by quartile, adjusting for demographics, poverty, insurance, smoking, checkups, region, and clustering of census tracts within counties. We also evaluated whether associations differed by social vulnerability and rurality.

Results. Compared with tracts in the farthest quartile, those in the closest quartile had higher adjusted prevalence of hypertension, heart disease, diabetes, chronic obstructive pulmonary disease, stroke, cancer, and chronic kidney disease; differences ranged from +0.047 to +0.224 prevalence points. Asthma prevalence was lower (−0.016 prevalence points). Proximity gradients were generally largest for hypertension and diabetes in highly socially vulnerable tracts. Although disease prevalence was often higher in nonmetropolitan areas, proximity gradients were not consistently stronger in nonmetropolitan than metropolitan tracts. Sensitivity analyses accounting for tract size, alternative rurality definitions, and spatial dependence produced generally directionally consistent results.

Conclusions. Greater toxic hazard proximity was associated with higher tract-level prevalence of several chronic diseases, although associations varied by outcome and community characteristics. Because this ecological, cross-sectional study cannot establish temporality or individual-level risk, the findings should be interpreted as evidence of community-level environmental health patterning. The results support the need for longitudinal and individual-level studies to inform monitoring, cleanup prioritization, and chronic disease prevention.

Trial registration

Clinical trial number: not applicable.

Background

Eight of the ten leading causes of death in the United States (U.S.) were chronic diseases in 2023.¹ The prevalence of chronic diseases such as cancer, heart disease, and diabetes is disproportionately higher in vulnerable communities, driven by poor social determinants of health, including limited insurance

coverage, disposable income, and access to health care.^{2–6} The etiology of chronic diseases is increasingly understood to be multifactorial, with both the genome and exposome including all types of exposures an individual will interact with throughout their life on disease development (i.e. biological, chemical, physical, psychological, relational, and socioeconomic factors).^{7–9} Under the purview of the exposome, exposures to environmental contaminants, particularly those found in toxic hazard sites (THS), are of increasing concern in the onset of chronic diseases.^{10–12}

The relationship between toxic hazard and chronic diseases is understudied, and most frequently investigated within specific site types. These include Superfund Sites, Environmental Protection Agency (EPA)-designated “uncontrolled” or “abandoned” locations requiring long-term cleanup. Superfund sites have been linked to adverse health outcomes, including birth defects, neurological deficits, and cancer.^{13–15} Far fewer studies have evaluated other THS categories, such as Risk Management Plan (RMP) facilities, Toxic Release Inventory (TRI) sites, or Treatment, Storage, and Disposal (TSD) facilities, despite evidence suggesting similar risks.^{16,17} Studies that do consider multiple site types have typically been limited to regional analyses or combined these exposures with other environmental hazards, as in Liu et al. (2024), who found that cumulative environmental burden was associated with higher cardiovascular disease prevalence, especially in socially vulnerable neighborhoods, but did not isolate the independent effect of THS proximity.¹⁸ Although it is well-known that THS are disproportionately located in high-SVI areas, little is known about how proximity to different THS subtypes affects chronic disease prevalence across varying levels of social vulnerability.^{19–21} Similarly, rural–urban differences in chronic disease burden are documented,^{22,23} but few studies have examined whether rurality modifies the impact of THS exposure.¹⁴ In high-SVI communities, limited resources, co-occurring environmental and social stressors, and reduced capacity for mitigation may heighten the health impact of THS exposure²⁴. In rural communities, reliance on private wells, less residential–industrial buffering²⁵, and less intensive monitoring/enforcement²⁶ may increase the likelihood that ecological proximity translates into personal exposure²⁷.

To address these gaps, we conducted a nationwide analysis of census tracts in the contiguous U.S. to evaluate the association between residential proximity to multiple types of THS and the prevalence of eight chronic diseases: coronary heart disease (CHD), stroke, hypertension, diabetes, asthma, chronic kidney disease (CKD), cancer, and chronic obstructive pulmonary disease (COPD). We further assessed whether these associations differed by neighborhood social vulnerability and rural–urban status. By isolating proximity to diverse THS subtypes on a national scale, our study provides new insight into the intersection of environmental exposures, structural inequities, and chronic disease burden.

Methods

Study Design and Data Sources:

This is an ecological, cross-sectional analysis of census tracts in the contiguous U.S., linking tract-level data on toxic hazard site exposure, chronic disease prevalence, and sociodemographic characteristics from publicly available sources (detailed descriptions, release years, and data source links provided in **Table S1**). Environmental exposure measures were derived from the CDC/Agency for Toxic Substances and Disease Registry (ATSDR) Environmental Justice Index (EJI, 2022). Health outcome data were obtained from the 2020 and 2021 Centers for Disease Control and Prevention (CDC) PLACES Project, based primarily on 2017–2019 Behavioral Risk Factor Surveillance System (BRFSS) survey data, U.S. Census 2010 population estimates, and American Community Survey (ACS) 2014–2019 data. Social vulnerability was assessed using the 2018 CDC/ATSDR Social Vulnerability Index (SVI), and rural–urban classification was based on 2010 U.S. Department of Agriculture (USDA) Rural–Urban Commuting Area (RUCA) codes. All datasets were linked at the census tract level using Federal Information Processing Series (FIPS) codes. Institutional review board approval was not required as all data were deidentified and publicly available.

Exposures:

Four environmental hazard indicators from the EJI were included: National Priorities List (NPL, Superfund) sites, TRI, TSD, and RMP sites. For each census tract, the EJI provides a national percentile rank for each of these indicators reflecting the tract’s relative proximity or burden compared to all other tracts nationwide. For each tract, percentile ranks for the four indicators were summed and re-ranked to create a cumulative proximity score from 0 to 100, with higher values indicating greater cumulative toxic hazard proximity. Quartiles of this score were used in the primary analysis, with quartile 4 (or Q4) corresponding to the closest proximity or highest toxic hazard site burden. In sensitivity analyses, we modeled the proximity score continuously per 10-point increase and evaluated whether results differed by census tract area.

Health Outcomes:

Primary outcomes were tract-level prevalence of CHD, stroke, hypertension, diabetes, asthma, CKD, cancer (excluding skin), and COPD, obtained through CDC PLACES (2020 and 2021 releases) and averaged across years to improve stability. CDC PLACES applies multilevel regression and poststratification to generate model-based small-area estimates using BRFSS (2017–2019), U.S. Census (2010), and ACS (2013–2019) data (**Table S1**).

Social Vulnerability and Rurality:

Neighborhood-level social vulnerability and rurality comprised potential moderators. Social vulnerability was measured using a composite SVI score, a percentile ranking based on 16 demographic and socioeconomic indicators grouped into four domains: socioeconomic status, household composition and disability, minority status and language, and housing and transportation. To facilitate interpretation and ensure adequate sample size per group, we categorized SVI into tertiles (low, moderate, and high)

based on its distribution across all census tracts. Rurality was defined according to the 2010 RUCA codes. Census tracts were classified as metropolitan (codes 1–3, representing urban cores and high-density commuting areas) or nonmetropolitan (codes 4–10, representing micropolitan, small town, and rural/isolated communities).

Adjustment Variables:

Statistical models further adjusted for tract-level covariates selected for their relevance to chronic disease risk and to potential confounding with toxic hazard site exposure. These included the percentage of uninsured individuals, percentage of residents from minoritized racial and ethnic groups, the percentage of adults aged 65 and older, and the percentage of residents below 200% of the federal poverty level, as well as the prevalence of current smoking and routine checkups. Demographic and socioeconomic covariates were obtained from the EJI, while smoking and routine checkup prevalence were obtained from CDC PLACES. Details on data sources for these covariates are provided in **Table S1**. Region (Northeast, Midwest, South, West; U.S. Census Bureau definitions) and tract population size were also included.

Statistical analysis:

We summarized census tract characteristics across quartiles of THS proximity using medians and interquartile ranges for continuous variables and proportions for categorical variables. The association between THS proximity and the prevalence of chronic diseases was estimated using mixed-effects linear regression models. Both unadjusted and adjusted models were fitted. The unadjusted model included toxic hazard site proximity quartile as the exposure variable and a county-level random intercept to account for clustering of census tracts within counties. Adjusted models included the following tract-level covariates: percentage of uninsured individuals, percentage of residents from minoritized racial and ethnic groups, percentage of adults aged 65 and older, percentage below 200% of the federal poverty level, prevalence of current smoking, prevalence of recent checkups, and geographic region (Northeast, Midwest, South, West). All models were weighted by total tract population. To assess potential effect modification, separate models were fitted with interaction terms between toxic hazard site proximity and either social vulnerability tertile or rurality category. Results are reported as estimated differences in chronic disease prevalence (percentage points) between each quartile of toxic hazard site proximity, with the lowest exposure quartile (quartile 1) serving as the reference group. Adjusted marginal means and 95% confidence intervals were calculated for each exposure quartile and for each subgroup defined by social vulnerability or rurality. Because the large sample size could make small interaction effects statistically significant, effect modification was interpreted using both interaction tests and absolute Q4–Q1 prevalence differences within strata. Sensitivity analyses modeled toxic hazard proximity continuously per 10-point increase, repeated models after excluding the largest 10% of census tracts by land area, stratified associations by tract-area tertile, and examined refined RUCA categories. Because area-level environmental and health data may exhibit spatial dependence, we also assessed residual spatial autocorrelation from the adjusted mixed-effects models using Moran's I with a six-nearest-neighbor tract-level spatial weights matrix. We then fitted spatial Durbin models using a symmetric six-

nearest-neighbor spatial weights matrix to evaluate whether the primary associations were robust to spatial dependence among neighboring census tracts. All statistical tests were two-sided, and a p-value less than 0.05 was considered statistically significant. All analyses were conducted using R version 4.4.1.

Results

Geographic Distribution of Toxic Hazard Site Proximity and Chronic Disease Prevalence:

The final sample included 71,638 U.S. Census tracts, representing 98% of all eligible tracts after excluding tracts in Alaska, Hawaii, and U.S. territories. The spatial distribution of toxic hazard site proximity quartiles is shown in Fig. 1. Higher proximity quartiles were proportionally more common in the Northeast and Midwest than in the South or West, although the map showed visually prominent high-proximity tracts in some large-area western regions. Because census tracts vary substantially in land area, visual prominence on the map should not be interpreted as proportional to the number of affected residents or tracts. The geographic distributions of tract-level chronic disease prevalence are shown in **Figure S1**, with each panel displaying within-outcome prevalence quartiles to facilitate comparison of spatial patterning across diseases with different absolute prevalence ranges.

Sociodemographic Characteristics by Proximity Quartile:

Table 1 summarizes the sociodemographic characteristics of census tracts by quartile of toxic hazard site proximity. Compared to Q1, Q4 tracts had higher median percentage of residents from minoritized racial and ethnic groups (42.4% vs 24.7%), higher median percentage below 200% of the federal poverty level (37.1% vs 25.6%), higher smoking prevalence (18.9% vs 16.5%), higher percentage uninsured (8.0% vs 6.4%), and higher SVI score (0.64 vs 0.39), and lower percentage aged ≥ 65 years (13.6% vs 17.0%). Q4 tracts were more common among metropolitan tracts than nonmetropolitan tracts (27.1% vs 15.3%), whereas nonmetropolitan tracts were concentrated more in Q3 than Q4 (31.0% vs 15.3%). Regionally, the proportion of tracts classified in Q4 was highest in the Northeast (30.3%) and Midwest (29.5%).

Table 1

Sociodemographic and Health-Related Characteristics of Census Tracts by Toxic Hazard Site Proximity Quartile. Values are median (interquartile range) for continuous tract-level variables and n (%) for categorical variables. Toxic hazard proximity quartiles were based on the cumulative percentile score for National Priorities List, Toxic Release Inventory, Treatment, Storage, and Disposal, and Risk Management Plan site indicators. Q1 indicates lowest proximity burden and Q4 indicates highest proximity burden.

Variable	Proximity to Toxic Exposure Sites, Median (IQR)			
(n = 71,638)	Q1 (n = 17907)	Q2 (n = 17907)	Q3 (n = 17914)	Q4 (n = 17910)
Residents from minoritized racial and ethnic groups (%)	24.7 (10.6, 50.3)	25.3 (11.0, 51.5)	30.1 (11.72, 62.5)	42.35 (19.8, 76.1)
Smoking (%)	16.5 (12.75, 20.65)	17.3 (13.55, 21.35)	18.05 (14.35, 21.8)	18.85 (14.95, 23.35)
Checkup prevalence (%)	76.5 (72.6, 79.2)	76.6 (73.0, 79.25)	76.45 (2.8, 79.05)	76.15 (71.9, 79.1)
Uninsured (%)	6.4 (3.5, 11.1)	6.5 (3.6, 11.25)	7.2 (4.0, 11.6)	8.0 (4.4, 13.6)
Poverty below 200 (%)	25.6 (14.8, 38.9)	27.7 (16.6, 40.9)	31.3 (20.04, 45.4)	37.1 (23.2, 53.3)
Age > = 65 (%)	17.0 (12.5, 21.8)	16.3 (12.3, 20.4)	15.7 (11.4, 19.8)	13.6 (9.8, 18.0)
SVI	0.39 (0.17, 0.63)	0.45 (0.22, 0.69)	0.53 (0.28, 0.76)	0.64 (0.36, 0.85)
Northeast	2439 (18.3%)	2439 (18.3%)	3704 (27.8%)	4045 (30.3%)
Midwest	2901 (17.1%)	4266 (25.2%)	4773 (28.2%)	4989 (29.5%)
South	7451 (28.7%)	6899 (26.6%)	6115 (23.6%)	5485 (21.1%)
West	5116 (33.2%)	3599 (23.3%)	3322 (21.5%)	3391 (22%)
Metro	14521 (24.7%)	14384 (24.5%)	13920 (23.7%)	15947 (27.1%)
Non-metro	3386 (26.3%)	3523 (27.4%)	3994 (31%)	1963 (15.3%)

Associations Between Toxic Hazard Site Proximity and Chronic Disease Prevalence:

In unadjusted models, when compared to Q1, U.S. Census tracts closest to THS (Q4) had higher prevalence of CHD, CKD, COPD, asthma, diabetes, and hypertension. For cancer, however, the unadjusted association was inverse, with Q4 tracts having lower prevalence compared to Q1 (Fig. 2). After adjustment, Q4 versus Q1 differences remained statistically significant for all outcomes, although estimates were generally attenuated and asthma changed direction. In adjusted models, Q4 versus Q1 prevalence-point differences were positive but small for hypertension (+ 0.224), CHD (+ 0.105), diabetes (+ 0.098), COPD (+ 0.083), stroke (+ 0.075), cancer (+ 0.063), and CKD (+ 0.047), and slightly negative for

asthma (-0.016) (**Table S2**). Continuous exposure models showed similar patterns, with small adjusted prevalence-point differences per 10-point increase in toxic hazard proximity score (**Table S3**). The reversal of the cancer association after adjustment, and the attenuation or reversal of several other estimates, indicated substantial confounding by tract-level social and regional characteristics.

Effect Modification by Social Vulnerability:

Interaction tests suggested variation by Social Vulnerability Index (SVI), but absolute Q4–Q1 differences were modest and varied by outcome. Q4–Q1 differences were most consistently largest in high-SVI tracts, particularly for hypertension ($+0.369$ prevalence points), diabetes ($+0.302$), coronary heart disease ($+0.119$), and stroke ($+0.091$). However, patterns were not uniform across outcomes; for example, asthma showed negative Q4–Q1 differences across SVI strata. Stratified marginal prevalences and Q4–Q1 differences are shown in Table 2 and Fig. 3.

Table 2

Adjusted Marginal Prevalence and Q4–Q1 Differences by Toxic Hazard Site Proximity, Social Vulnerability, and Rurality. Models adjusted for percentage uninsured, percentage of residents from minoritized racial and ethnic groups, percentage aged ≥ 65 years, percentage below 200% of the federal poverty level, current smoking prevalence, routine checkup prevalence, U.S. Census region, and county-level random intercepts. Values are adjusted marginal prevalence estimates with 95% confidence intervals unless otherwise indicated.

Outcome	SVI/ Rurality	Q1	Q2	Q3	Q4	Q4 minus Q1
CANCER	Low SVI	6.63 (6.60, 6.66)	6.67 (6.64, 6.70)	6.65 (6.62, 6.68)	6.64 (6.61, 6.68)	0.013
	Medium SVI	6.83 (6.80, 6.86)	6.86 (6.83, 6.89)	6.84 (6.81, 6.87)	6.87 (6.84, 6.90)	0.036
	High SVI	7.09 (7.06, 7.13)	7.13 (7.10, 7.16)	7.11 (7.08, 7.14)	7.16 (7.12, 7.19)	0.062
	Metro	6.81 (6.77, 6.84)	6.84 (6.81, 6.87)	6.81 (6.78, 6.85)	6.85 (6.82, 6.88)	0.048
	Non-metro	6.83 (6.80, 6.86)	6.96 (6.93, 7.00)	6.98 (6.94, 7.01)	7.00 (6.96, 7.04)	0.172
CKD	Low SVI	3.00 (2.99, 3.02)	3.02 (3.01, 3.04)	3.03 (3.01, 3.04)	3.03 (3.01, 3.05)	0.026
	Medium SVI	2.98 (2.97, 3.00)	3.00 (2.98, 3.01)	2.99 (2.98, 3.01)	3.00 (2.99, 3.02)	0.022
	High SVI	3.10 (3.08, 3.11)	3.13 (3.12, 3.15)	3.14 (3.13, 3.16)	3.17 (3.16, 3.19)	0.079
	Metro	3.00 (2.99, 3.02)	3.02 (3.01, 3.04)	3.02 (3.01, 3.04)	3.05 (3.03, 3.07)	0.043
	Non-metro	3.03 (3.01, 3.05)	3.08 (3.07, 3.10)	3.08 (3.06, 3.10)	3.10 (3.08, 3.12)	0.074
Asthma	Low SVI	10.04 (10.01, 10.07)	10.02 (9.98, 10.05)	10.03 (10.00, 10.06)	10.03 (10.01, 10.06)	-0.006
	Medium SVI	9.98 (9.96, 10.01)	10.00 (9.97, 10.03)	9.99 (9.97, 10.02)	9.98 (9.95, 10.00)	-0.004
	High SVI	9.96 (9.93, 9.98)	9.97 (9.94, 9.99)	9.93 (9.91, 9.96)	9.94 (9.91, 9.96)	-0.024
	Metro	10.01 (9.98, 10.03)	10.00 (9.98, 10.03)	10.01 (9.97, 10.03)	9.96 (9.93, 10.00)	-0.021
	Non-metro	9.97 (9.94, 10.01)	9.98 (9.95, 10.01)	9.97 (9.94, 10.00)	10.01 (9.97, 10.04)	0.032

Outcome	SVI/ Rurality	Q1	Q2	Q3	Q4	Q4 minus Q1
COPD	Low SVI	6.97 (6.94, 7.01)	7.02 (6.98, 7.05)	7.02 (6.98, 7.05)	7.04 (7.01, 7.08)	0.071
	Medium SVI	7.15 (7.11, 7.18)	7.14 (7.10, 7.17)	7.13 (7.10, 7.17)	7.17 (7.14, 7.21)	0.023
	High SVI	7.42 (7.39, 7.46)	7.48 (7.45, 7.52)	7.46 (7.43, 7.50)	7.51 (7.48, 7.55)	0.088
	Metro	7.09 (7.06, 7.13)	7.13 (7.10, 7.17)	7.13 (7.09, 7.17)	7.17 (7.13, 7.20)	0.073
	Non-metro	7.23 (7.19, 7.27)	7.32 (7.28, 7.36)	7.29 (7.26, 7.33)	7.38 (7.34, 7.43)	0.154
CHD	Low SVI	6.30 (6.26, 6.34)	6.35 (6.32, 6.39)	6.35 (6.32, 6.39)	6.37 (6.33, 6.40)	0.068
	Medium SVI	6.48 (6.44, 6.51)	6.48 (6.45, 6.51)	6.47 (6.44, 6.51)	6.52 (6.48, 6.55)	0.045
	High SVI	6.82 (6.78, 6.86)	6.87 (6.84, 6.91)	6.88 (6.84, 6.92)	6.95 (6.90, 6.97)	0.119
	Metro	6.40 (6.37, 6.44)	6.44 (6.41, 6.47)	6.45 (6.41, 6.48)	6.50 (6.47, 6.54)	0.101
	Non-metro	6.62 (6.58, 6.66)	6.72 (6.68, 6.75)	6.71 (6.67, 6.74)	6.73 (6.69, 6.78)	0.113
Stroke	Low SVI	3.47 (3.44, 3.50)	3.51 (3.48, 3.53)	3.52 (3.49, 3.54)	3.55 (3.52, 3.57)	0.076
	Medium SVI	3.47 (3.44, 3.49)	3.49 (3.47, 3.52)	3.49 (3.46, 3.52)	3.51 (3.49, 3.54)	0.044
	High SVI	3.59 (3.57, 3.62)	3.65 (3.62, 3.67)	3.65 (3.62, 3.67)	3.68 (3.66, 3.71)	0.091
	Metro	3.47 (3.44, 3.50)	3.50 (3.48, 3.53)	3.51 (3.48, 3.54)	3.54 (3.51, 3.57)	0.071
	Non-metro	3.52 (3.49, 3.55)	3.60 (3.57, 3.62)	3.59 (3.56, 3.61)	3.63 (3.60, 3.66)	0.109
Hypertension	Low SVI	33.05 (32.90, 33.21)	33.17 (33.02, 33.33)	33.22 (33.06, 33.37)	33.20 (33.04, 33.36)	0.147
	Medium SVI	33.21 (33.06, 33.37)	33.25 (33.09, 33.40)	33.24 (33.09, 33.39)	33.27 (33.11, 33.42)	0.054

Outcome	SVI/ Rurality	Q1	Q2	Q3	Q4	Q4 minus Q1
	High SVI	33.66 (33.50, 33.81)	33.84 (33.69, 34.00)	33.90 (33.75, 34.05)	34.03 (33.87, 34.18)	0.369
	Metro	33.19 (33.03, 33.35)	33.29 (33.13, 33.45)	33.32 (33.16, 33.48)	33.42 (33.27, 33.57)	0.231
	Non- metro	33.37 (33.21, 33.53)	33.60 (33.45, 33.76)	33.60 (33.44, 33.75)	33.47 (33.31, 33.64)	0.098
Diabetes	Low SVI	11.39 (11.33, 11.46)	11.43 (11.36, 11.49)	11.45 (11.38, 11.51)	11.40 (11.33, 11.47)	0.005
	Medium SVI	11.11 (11.04, 11.17)	11.11 (11.04, 11.17)	11.10 (11.04, 11.17)	11.09 (11.02, 11.16)	-0.015
	High SVI	11.37 (11.30, 11.44)	11.49 (11.42, 11.55)	11.58 (11.52, 11.65)	11.67 (11.60, 11.73)	0.302
	Metro	11.21 (11.15, 11.27)	11.24 (11.18, 11.31)	11.28 (11.22, 11.35)	11.32 (11.26, 11.38)	0.105
	Non- metro	11.34 (11.27, 11.42)	11.42 (11.35, 11.49)	11.41 (11.34, 11.48)	11.36 (11.28, 11.44)	0.015

Effect Modification by Rurality:

Adjusted marginal prevalence was generally higher in nonmetro than metro tracts for most outcomes, but Q4–Q1 proximity gradients were not consistently larger in nonmetro areas. Q4–Q1 gradients were larger in nonmetro tracts for cancer, chronic kidney disease, asthma, chronic obstructive pulmonary disease, coronary heart disease, and stroke, whereas gradients were larger in metro tracts for hypertension and diabetes (Table 2; Fig. 3).

Sensitivity analyses stratified by tract-area tertile and excluding the largest 10% of census tracts by land area showed broadly similar patterns, although effect estimates varied somewhat by tract size (**Tables S4 and S5**). Sensitivity analyses using refined RUCA categories also showed that marginal prevalence patterns varied across metropolitan core, metropolitan commuting, micropolitan or small-town, and rural or isolated tracts, but did not indicate uniformly stronger proximity gradients in the most rural categories (**Table S6**). Residual spatial autocorrelation was present in the adjusted mixed-effects models, with Moran's I ranging from 0.225 for COPD to 0.360 for diabetes (**Table S7**). In spatial Durbin sensitivity

models using a symmetric six-nearest-neighbor tract-level spatial weights matrix, the direct Q4 versus Q1 toxic hazard proximity estimates were directionally consistent with the primary adjusted models across outcomes (**Table S8**). Several estimates were attenuated after accounting for spatial dependence, particularly hypertension and diabetes, indicating that spatial clustering contributed to the observed ecological associations while not materially changing the overall direction of the findings.

Discussion

In this national, ecological, cross-sectional study, census tracts closer to toxic hazard sites had a higher prevalence of multiple chronic diseases, even after adjustment for sociodemographic, poverty, health care access, behavioral, and regional factors. The largest prevalence differences were observed for hypertension, CHD and diabetes, while smaller differences were observed for COPD, stroke, cancer, and CKD; asthma showed a slight negative adjusted association. Associations were modest in magnitude and sensitive to adjustment, underscoring the importance of social and regional confounding in ecological environmental health analyses. Gradients by social vulnerability and rurality varied by outcome, with the clearest larger Q4–Q1 differences in high-SVI tracts observed for hypertension and diabetes. Prior work shows that socially vulnerable communities are more likely to live near workplace hazard exposures^{28,29}, heavy metal exposures³⁰, as well as other personal toxic exposures³¹. These cumulative risks may help explain the higher chronic disease burden observed in high-SVI areas.

Nonmetro tracts had higher adjusted marginal prevalence for many outcomes, but the proximity gradient was not consistently stronger in nonmetro areas. This distinction is important because higher baseline disease burden in nonmetro communities does not necessarily imply stronger proximity–disease associations. These findings support considering rurality in environmental health analyses, while also cautioning against interpreting rurality as a uniform modifier of toxic hazard proximity.

Our results extend prior environmental justice research by simultaneously assessing proximity to multiple types of hazard sites nationwide.^{14,16,32} Most previous studies focused on a single site (e.g., Superfund or TRI facilities) or region, limiting generalizability. By integrating diverse site classes and examining both social vulnerability and rurality, our study reinforces and expands upon the findings of Liu et al (2024), which reported stronger associations between cumulative environmental burden and cardiovascular disease in vulnerable neighborhoods. We build upon this by investigating multiple chronic disease outcomes. However, because estimates were small and attenuation after adjustment was substantial, these results should be interpreted as tract-level evidence of environmental health patterning rather than as evidence of individual-level toxicologic effects.^{10,33}

While causal inference is limited in observational designs, including the ecological cross-sectional study design used in this analysis, our findings align with prior research supporting hypothesized exposure pathways identified in prior literature. For example, Kouznetsova et al. (2007) conducted an ecological cross-sectional study at the ZIP code level, finding that inhaled or ingested airborne contaminants likely explained the association between proximity to New York State Superfund sites and type 2 diabetes.³⁴

Ala et al. (2006) performed an ecological analysis of ZIP code–level prevalence of chronic autoimmune liver disease near Superfund sites and implicated airborne contamination, while downplaying groundwater ingestion because few residents relied on wells.³⁵ In contrast, Borowsky et al. (2025) used a mixed ecological–individual cross-sectional design and identified groundwater and soil contamination, rather than air, as the primary exposure pathways linking Superfund site proximity and metastatic breast cancer in southern Florida.³⁶ This study also found no modification by income or healthcare access. Finally, Bulka et al. (2016) conducted a spatial ecological study and reported that proximity to TRI sites was associated with increased incidence of Diffuse Large B-Cell Lymphoma; in their study, race modified associations, whereas income did not.³⁷ Our study extends these findings by incorporating social vulnerability, which includes the minority status and language domain, as a potential modifier.

Our study highlights the importance of community-level strategies to address the challenges brought forth by these toxic exposure sites. Future individual-level studies are needed to determine how environmental exposures translate into personal health risk, which would subsequently inform clinical and patient-level approaches. At the policy level, enhanced monitoring and transparency around toxic sites, especially around their impact on local communities, is essential³⁸. This would inform evidence-based policies around cleanup and effective resource allocation³⁹. Public awareness should prioritize high-risk, socially vulnerable, and rural communities. Finally, strengthened federal and state regulations⁴⁰, and community participation⁴¹ in site planning can help prevent future disproportionate exposure.

This study has several limitations. First, the use of census tracts as the unit of analysis introduces the potential for ecological fallacy, where population-level associations may not reflect individual-level risk. Within-tract heterogeneity may also mask variation in exposures and outcomes among residents. While we adjusted for covariates (poverty, healthcare access, demographic factors, socioeconomic status, rurality, and social vulnerability), there may have been other essential confounders that were not accounted for. The substantial attenuation of estimates after adjustment, including reversal of the cancer and asthma associations, suggests that residual confounding by social, structural, regional, or environmental co-exposures remains possible. Second, the cross-sectional design prevents assessment of temporality, limiting causal interpretation. Because chronic disease prevalence reflects cumulative disease processes and toxic hazard proximity was measured cross-sectionally, we cannot determine whether exposure preceded disease development. Third, the results of this study are not generalizable to individual counties in the U.S. that differ in their sociodemographic characteristics and built infrastructure. Individual-level inferences cannot be made. Fourth, there are measurement limitations as we used cumulative EJI percentile scores to represent toxic hazard site exposure. This method may misclassify exposure by treating tracts with very different absolute proximities as similar once re-ranked, by assuming equal contribution of distinct site types when summed, and by assigning the same exposure score to all residents within a tract despite potential variation in proximity. Additionally, toxic hazard sites vary widely in the types, quantities, and mixtures of chemicals they contain, and these chemical profiles differ both across site types and within individual sites. Because specific contaminants

may have specific health effects, aggregating diverse sites into a single cumulative proximity metric may dilute or mask associations for pathways tied to particular toxicants. However, this approach provides a standardized national metric that enables comparison across all census tracts in the U.S. Fifth, CDC PLACES outcomes are model-based small-area estimates rather than direct disease measurements, and uncertainty in those estimates was not propagated into the regression models. Sixth, county random intercepts account for within-county clustering but do not fully address spatial autocorrelation between neighboring tracts. Spatial sensitivity analyses produced directionally consistent findings, but estimates may depend on the specified spatial weights matrix, and several spatially lagged coefficients had unstable standard errors. Finally, linear models were used to estimate prevalence-point differences for bounded prevalence outcomes; results should therefore be interpreted as population-level prevalence differences rather than individual-level risks. Because we evaluated multiple outcomes and interaction terms, some statistically significant findings may reflect multiple testing. We therefore emphasized effect sizes, confidence intervals, and consistency of patterns rather than statistical significance alone.

Conclusion

This national ecological study found that census tracts closer to toxic hazard sites had higher adjusted prevalence of several chronic diseases compared with tracts farther from these sites. These findings underscore the importance of identifying how environmental exposures and social conditions jointly shape chronic disease burden at the community level. Future research should clarify the specific contaminants, exposure pathways, and co-occurring social risks that may drive these associations. Longitudinal and individual-level studies are needed to better establish temporality, evaluate biological and environmental mechanisms, and identify communities most at risk. In addition, evaluating how monitoring, cleanup, and mitigation strategies influence community-level health may help guide policy priorities. Ultimately, reducing the health burden associated with toxic hazard sites will require coordinated local, state, and federal action to advance environmental justice, strengthen environmental monitoring, and align cleanup efforts with chronic disease prevention.

Abbreviations

ACS

American Community Survey

ATSDR

Agency for Toxic Substances and Disease Registry

BRFSS

Behavioral Risk Factor Surveillance System

CDC

Centers for Disease Control and Prevention

CHD

coronary heart disease

CKD

chronic kidney disease
COPD
chronic obstructive pulmonary disease
EJI
Environmental Justice Index
EPA
Environmental Protection Agency
FIPS
Federal Information Processing Series
NPL
National Priorities List
RMP
Risk Management Plan
RUCA
Rural–Urban Commuting Area
SVI
Social Vulnerability Index
THS
toxic hazard sites
TRI
Toxic Release Inventory
TSD
Treatment, Storage, and Disposal
USDA
United States Department of Agriculture.

Declarations

Ethics approval and consent to participate

Not applicable. This study used publicly available, deidentified, aggregate census-tract data and did not involve individual human participants or identifiable individual-level information. Institutional review board approval and informed consent were therefore not required.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

A.M.A. and S.M.Q.H. conceived and designed the study and drafted the main manuscript text. A.M.A. contributed to data acquisition and analysis, interpreted the findings, and prepared Figures 1–3. O.F.B., S.T., K.P.G., J.K.W., E.B.L., A.H.H., G.B.R., and H.B.R. contributed to the interpretation of the findings and critically revised the manuscript for important intellectual content. S.M.Q.H. provided senior supervision. All authors reviewed and approved the final manuscript.

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Data Availability

All datasets analyzed in this study are publicly available. Chronic disease prevalence estimates were obtained from the Centers for Disease Control and Prevention PLACES Project. Toxic hazard proximity measures were obtained from the CDC/Agency for Toxic Substances and Disease Registry Environmental Justice Index. Social vulnerability measures were obtained from the CDC/ATSDR Social Vulnerability Index, and rurality classifications were obtained from the U.S. Department of Agriculture Rural–Urban Commuting Area codes. Detailed descriptions of the datasets, variables, release years, and access sources are provided in the Supplementary Information file, Table S1.

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Figures

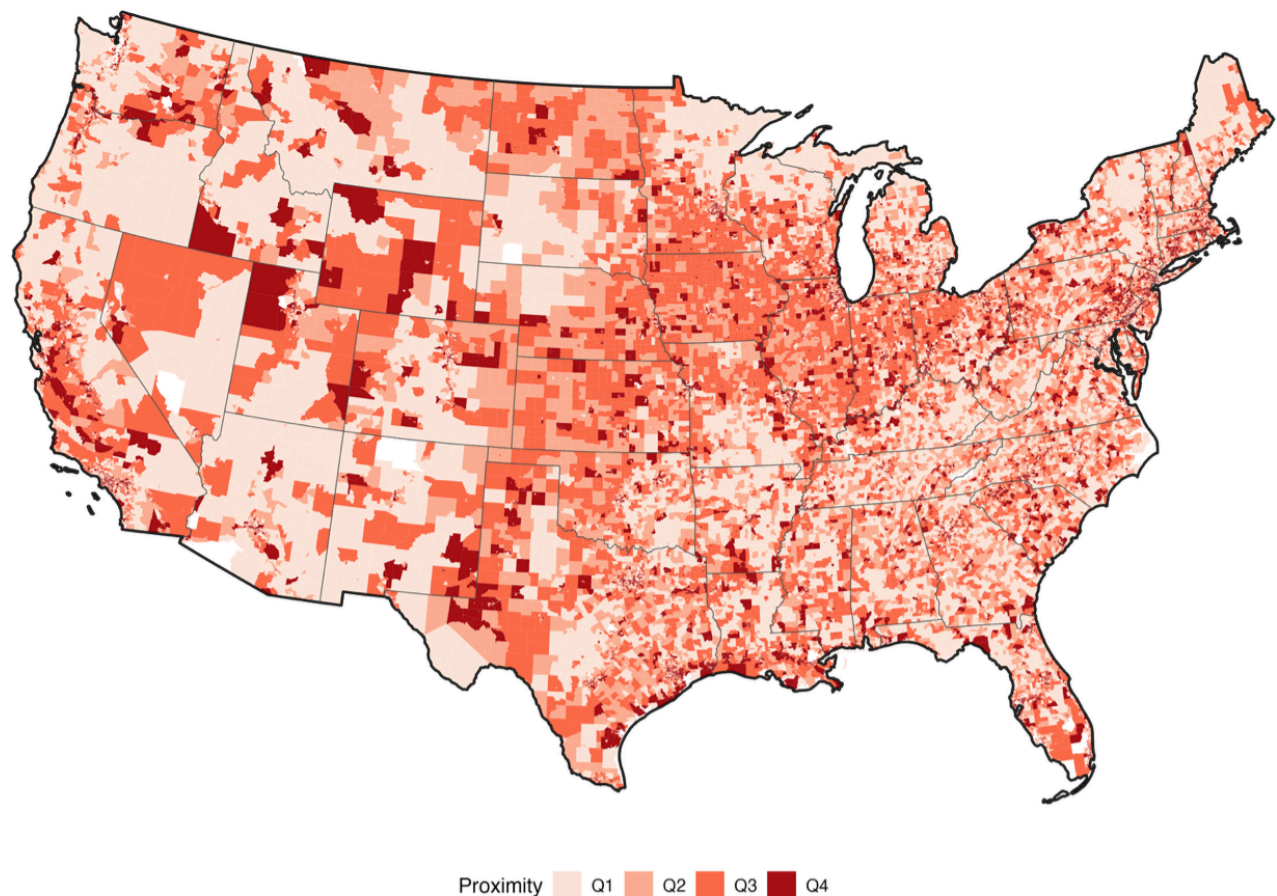


Figure 1

Census Tract Quartiles of Proximity to Toxic Hazard Sites in the United States. Census tracts are categorized into quartiles of cumulative toxic hazard site proximity, with Q1 representing the lowest proximity burden and Q4 representing the highest. Lighter colors indicate lower proximity burden and darker colors indicate higher proximity burden. Because census tracts vary substantially in land area, visual prominence on the map should not be interpreted as proportional to the number of affected residents or tracts.

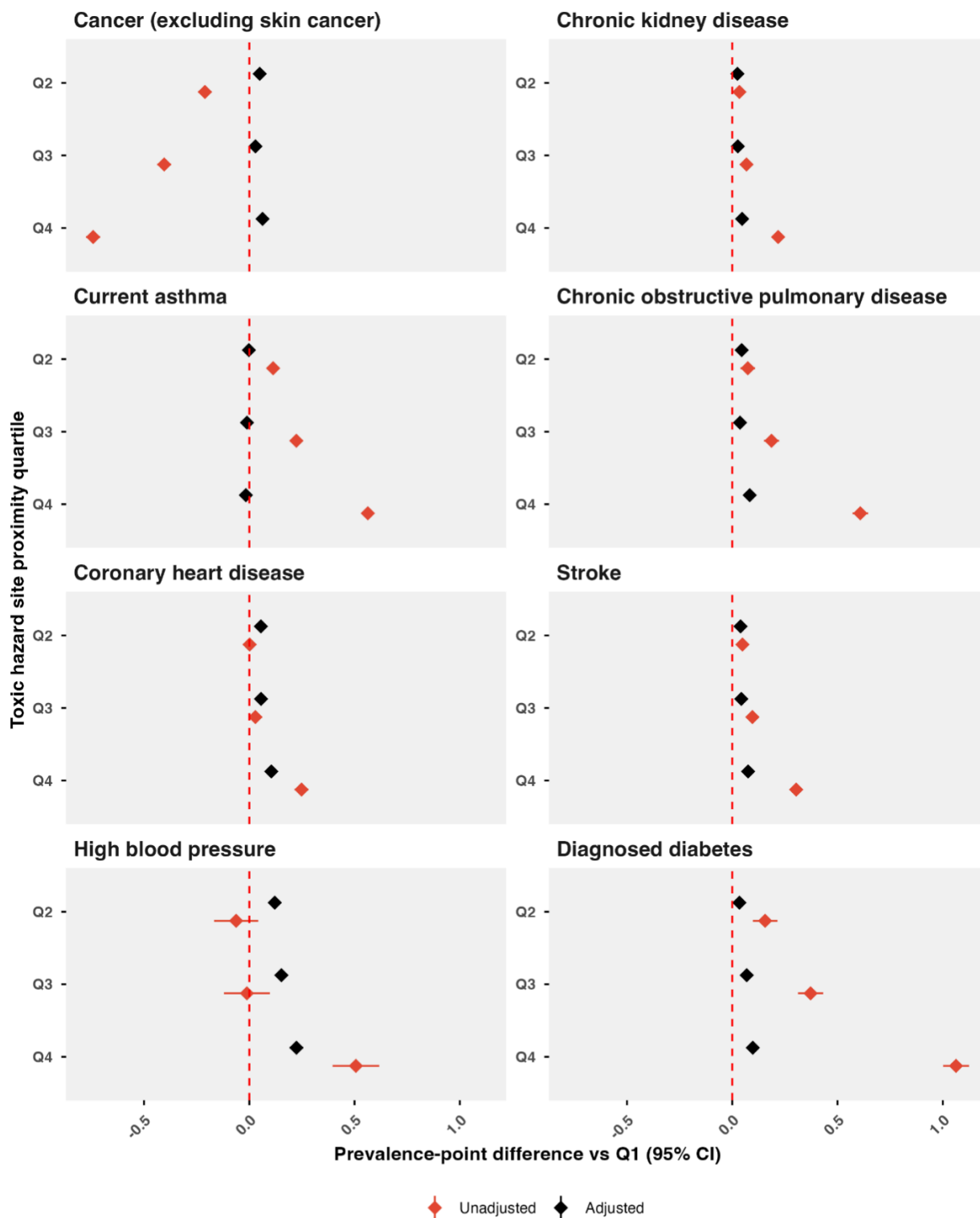


Figure 2

Estimated Differences in Chronic Health Outcomes by Census Tract Proximity to Toxic Hazard Sites. Estimated prevalence-point differences in chronic disease prevalence by toxic hazard site proximity quartile. Q1 is the reference group. Adjusted models included percentage uninsured, percentage of residents from minoritized racial and ethnic groups, percentage aged ≥ 65 years, percentage below 200% of the federal poverty level, current smoking prevalence, routine checkup prevalence, U.S. Census region,

and county-level random intercepts. Points represent prevalence-point differences and error bars indicate 95% confidence intervals. The dashed line indicates no difference from Q1.

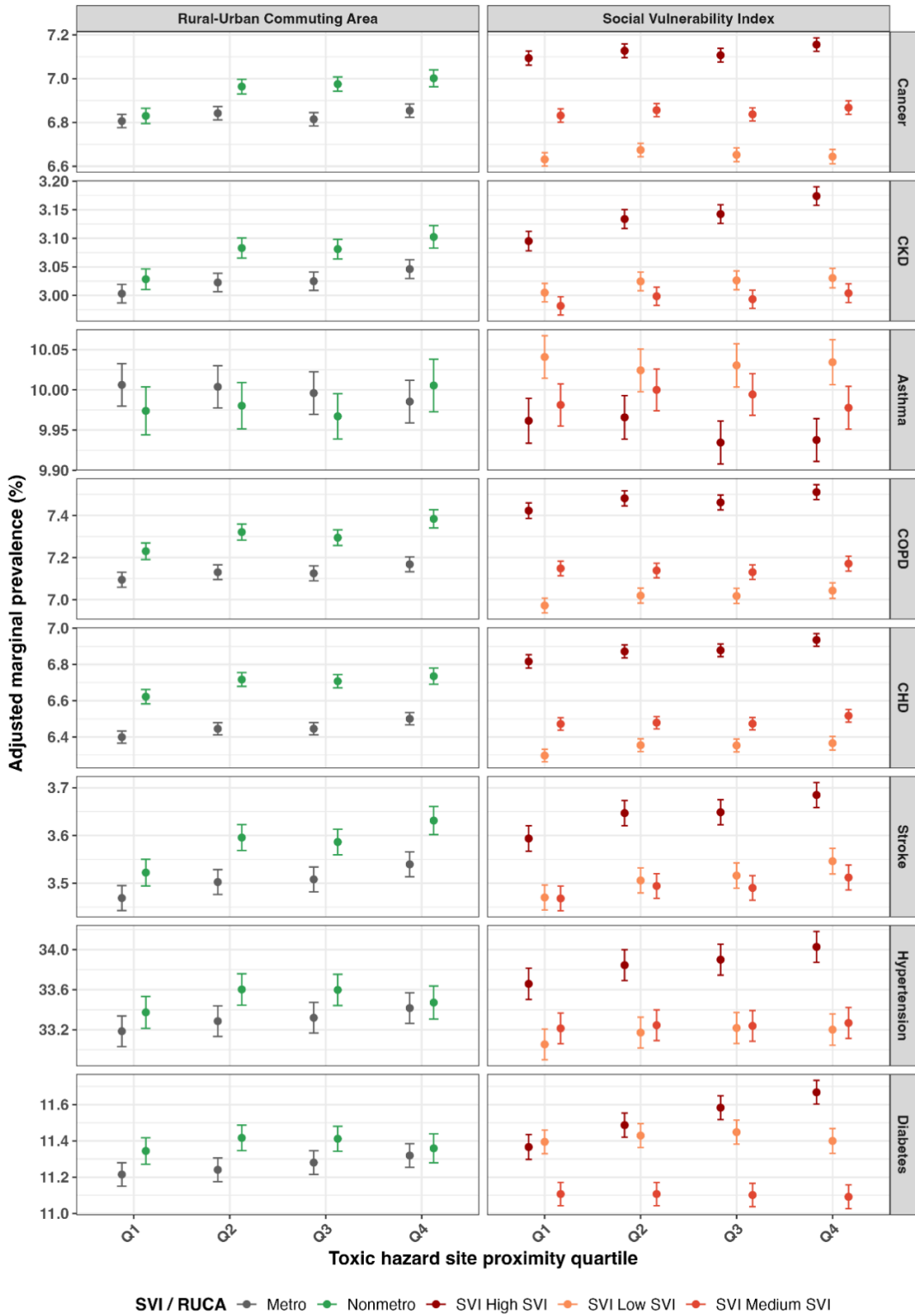


Figure 3

Estimated Marginal Mean Prevalence of Chronic Health Outcomes by Toxic Hazard Site Proximity, Stratified by Social Vulnerability and Rurality. Adjusted marginal prevalence of chronic disease outcomes

by toxic hazard site proximity quartile, stratified by Social Vulnerability Index tertile and Rural–Urban Commuting Area category. Models adjusted for percentage uninsured, percentage of residents from minoritized racial and ethnic groups, percentage aged ≥ 65 years, percentage below 200% of the federal poverty level, current smoking prevalence, routine checkup prevalence, U.S. Census region, and county-level random intercepts. Points represent adjusted marginal prevalence estimates and error bars indicate 95% confidence intervals.

Supplementary Files

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