

<https://doi.org/10.1038/s44432-025-00005-x>

# Heat and air pollution shape divergent mortality patterns across rural and urban United States

Check for updates

Shuai Zhou<sup>1,2</sup>, Chuan Liao<sup>1</sup> ✉, Ziqing Wei<sup>3</sup> & Guangqing Chi<sup>4</sup>

The pathogenic causes and social determinants of death have been extensively explored; however, the role of environmental factors in shaping mortality disparities remains underexamined. By linking mortality with climate data and sociodemographic information from 2009 through 2019, we explored the impacts of temperature, air quality, and their interactions on cause- and age-specific mortality at the county level in the United States over the past decade. We found an environment-induced rural paradox and urban penalty, alongside the well-documented rural mortality penalty. Specifically, as temperatures and PM<sub>2.5</sub> levels increased, rural areas faced a cardiovascular mortality penalty among infants, while a rural paradox in respiratory mortality emerged, with lower respiratory mortality observed in rural areas. Additionally, we observed an urban respiratory mortality penalty among working-age adults under increasing temperatures and worsening air pollution conditions. The findings emphasized the critical role of environmental conditions in shaping health disparities and underscored the importance of targeted public health interventions.

Multiple causes can lead to poor health outcomes, premature, and preventable mortality. For one, mortality is closely related to pathogens and malfunctions of human organs caused by such pathogenic infections. For another, health issues and subsequent mortality are also connected to social factors. Evidence from public health research has shown that 40% to 80% of health issues can be attributed to social factors<sup>1,2</sup>. Together, these conceptual insights and empirical evidence have converged to a framework that urges researchers and policymakers to reassess population health through the social determinants of health (SDH) framework. The SDH framework encompasses a wide range of factors, such as socioeconomic status, education, employment opportunities, housing, healthcare, and social connection<sup>3</sup>. Those factors significantly influence individuals' and groups' overall health and well-being, often showing more profound impacts on health and health equity than clinical factors, as reflected in empirical evidence from studies across the globe<sup>4-8</sup>.

However, the SDH framework primarily focuses on social and economic influences on health while often overlooking the role of environmental factors, which are intricately linked to population health. Shifts in climate patterns, increasing temperature and air pollution, and alterations in ecosystems can both directly and indirectly harm human health<sup>9,10</sup>. For example, extreme heat can directly cause death through dehydration,

cardiovascular strain, and multi-organ failure<sup>11</sup>. Air quality, usually measured by inhalable particulate matter such as PM<sub>2.5</sub>, has also an impact on population health, with studies from multiple countries demonstrating both short- and long-term exposure to PM<sub>2.5</sub> could cause detrimental effects leading to mortality<sup>12-16</sup>. Additionally, environmental changes can indirectly impact health by modifying exposure pathways and weakening natural disease-regulating mechanisms<sup>17</sup>. Deforestation, land use change, and associated biodiversity loss weaken ecosystem services that regulate disease transmission, increase human exposure to disease hosts and vectors, and facilitate the spread of both infectious and non-communicable diseases<sup>17,18</sup>. Indeed, the twenty-first century has witnessed a growing concern regarding the impact of environmental conditions on population health, particularly as environmental changes accelerate and pessimism grows regarding the feasibility of limiting global warming to 1.5 °C<sup>19</sup>. The concern that environmental changes could exacerbate health issues and increase public health burdens has motivated various research into the intricate relationships between environmental factors and human health outcomes. The exposome theory, a framework that emphasizes the environmental exposures across the life course, is particularly relevant to research on how the environment shapes health outcomes<sup>20,21</sup>. Unlike the static genome explanation, the exposome theory dynamically links diverse and evolving exposures such as

<sup>1</sup>Department of Global Development, Cornell University, Ithaca, NY, USA. <sup>2</sup>Department of Sociology, Anthropology, and Social Work; Stocks School of Marine and Environmental Science, University of South Alabama, Mobile, AL, USA. <sup>3</sup>Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China. <sup>4</sup>Environmental Demography Network, Department of Geography, Indiana University, Bloomington, IN, USA.

✉ e-mail: [cl824@cornell.edu](mailto:cl824@cornell.edu)

air pollution, extreme temperatures, diet, and lifestyle to health outcomes. Research has shown that much of the burden from many complex human diseases, such as cancer, cardiovascular disease, and respiratory illness, can be attributed to environmental exposures and the interaction between individuals' genes and the environment<sup>22</sup>.

While numerous studies have shown that environmental conditions significantly impact a wide range of population health outcomes, little research has integrated these dimensions into the broader SDH framework. Anthropogenic global warming is one of the significant contributors to population health issues<sup>23,24</sup>. A large-scale meta-analysis using data from 732 locations around the world to explore the association between heat exposure and mortality. The study found that a substantial proportion (37%) of heat-related deaths occurring during warm seasons can be attributed to the influence of anthropogenic environmental changes<sup>9</sup>. This noteworthy increase in mortality due to rising temperatures manifested across all continents, although the temperature's influence showed geographic variability, with southern and eastern European countries being particularly vulnerable to heat-related deaths. Another systematic review of related literature showed similar heterogeneity in heat-related mortality, demonstrating that heat effects were higher in areas closer to the equator, especially in areas characterized by low economic development, high population density, and aging populations<sup>25</sup>.

Air pollution is another environmental stressor that causes morbidity and mortality among people who have been exposed to it for a short period<sup>12</sup> and prolonged exposure<sup>13</sup>. The concentration of particulate matter at finer scales (e.g., PM<sub>10</sub>, PM<sub>2.5</sub>, and PM<sub>0.1</sub> with a diameter of 10, 2.5, and 0.1 micrometers, respectively) is commonly used to measure air pollution. A study analyzing the temporal trends of PM<sub>10</sub> and its influence on mortality revealed that exposure to PM<sub>10</sub> was associated with an increased risk of mortality, specifically related to cardiovascular and respiratory causes<sup>26</sup>. Ambient PM<sub>10</sub> imposed higher health risks when it occurred in conjunction with heat waves, significantly amplifying the risk of mortality<sup>27</sup>. PM<sub>2.5</sub> and ultrafine particles such as PM<sub>0.1</sub>, which have diameters small enough to penetrate the blood-brain barrier<sup>28</sup>, impose more detrimental effects on health outcomes such as neurological disorders<sup>29</sup> and infant mortality<sup>30,31</sup>. A nationwide assessment of PM<sub>2.5</sub> exposure and mortality in the US suggested that PM<sub>2.5</sub> increases cardiovascular and respiratory mortality, particularly among older adults, minorities, males, and disadvantaged populations in metropolitan areas<sup>32</sup>. Source-specific analyses have shown that PM<sub>2.5</sub> components from coal combustion, traffic, soil, and metals were associated with 3.1 million deaths out of a cohort of 15.4 million Medicare beneficiaries in the US between 2000 and 2008<sup>33</sup>. Collectively, these studies consistently demonstrated that exposure to air pollution was closely associated with increased mortality, which is particularly related to cardiovascular and respiratory causes.

Environmental factors have also exerted differential health impacts based on rural-urban status and exacerbated existing health disparities among disadvantaged populations. These disparities are most evident in the rural mortality penalty, where studies have shown higher mortality rates in rural areas compared to their urban counterparts in the US<sup>34–37</sup>. Urban areas, on the other hand, face distinct environmental health risks, particularly due to the urban heat island effect, which intensifies heat waves and increases heat-related mortality, especially among older adults<sup>38,39</sup>. Additionally, air pollution exposures vary across racial, age, and socioeconomic groups, with minorities, younger individuals, and those with lower socioeconomic status disproportionately affected by component-specific pollutants such as sulfate, nitrate, and ammonium<sup>40</sup>. Certain demographic groups are particularly vulnerable to environmental stressors, including infants, children, and individuals living below the poverty line, who have been shown to experience higher mortality rates than other demographic groups<sup>41,42</sup>.

In the US, existing environmental health studies have enhanced our understanding of the health consequences of environmental changes. Nevertheless, a public health lens remains underdeveloped, with insufficient integration of environmental and social dimensions of mortality. Additionally, they often overlook the heterogeneous impacts of environmental

factors on cause-specific health issues across demographic groups, including different age cohorts and populations across rural and urban contexts. Building upon the SDH framework, we added environmental variables to explore the environmental influences on county-level cause- and age-specific mortality, after adjusting for sociodemographic factors, in the US, from 2009 through 2019. This study offers the possibility of providing new and valuable insights into the complex interplay between environmental factors and population health. These findings may also contribute to the field of public health by guiding the future development and implementation of targeted intervention strategies to protect and improve the health of vulnerable populations and communities in the face of growing environmental challenges. Rural/non-metropolitan areas and urban/metropolitan areas are used interchangeably.

## Results

### Descriptive statistics

Mortality rates show clear cause- and age-specific patterns (Fig. 1). In general, cardiovascular (CV) death rates are higher for all age groups than chronic respiratory (CR) death rates, reflecting the fact that cardiovascular diseases are the leading cause of death in the US over recent decades<sup>43,44</sup>. Regarding mortality rates across age groups, both CR and CV death rates show similar age-specific patterns, with older adults having the highest mortality rates, followed by working-age adults and infants. Unsurprisingly, children and teenagers have the lowest CR and CV mortality rates.

Table 1 presents the descriptive results of the environmental and sociodemographic variables at the county level and *t*-test comparing rural and urban counties. The mean ambient temperature and ambient PM<sub>2.5</sub> concentration were 12.8 °C and 7.3 µg/m<sup>3</sup>, respectively. The average household income was \$65,670, while approximately half of the population had college degrees. Health insurance coverage stood at 85%. The poverty rate was 12%. Urban counties tended to have substantially larger populations than rural counties across all age groups. Regarding county classification by metropolitan status, 37% of the counties were categorized as urban (metropolitan) counties according to the 2013 rural-urban classification. The *t*-test results suggest statistically significant differences across all variables between rural and urban counties.

### Regression results

Table 2 presents the cause- and age-specific mortality model results across rural and urban counties in the US, controlling the selected SDH sociodemographic variables, including household income, education, health insurance, poverty, and age-specific population. We performed slope tests by estimating the marginal effects of temperature at different ambient PM<sub>2.5</sub> levels and in rural and urban counties. The results suggest that changes in slope were statistically significant ( $p < 0.05$ ) across most of the combinations of temperature, PM<sub>2.5</sub> levels, and rurality for each age group (Fig. A2). Joint Wald tests of the interaction term indicate that the relationship between temperature and mortality differed significantly ( $p < 0.05$ ) across PM<sub>2.5</sub> levels and between rural and urban counties.

Looking at environmental factors individually, we found that temperature was positively associated with CV mortality among infants (age 0–1) and working-age adults (age 15–64), but had a negative association with CV mortality among children and adolescents (age 1–14) and older adults (age 65+). Meanwhile, temperature significantly increased CR mortality across all age groups. Similarly, ambient PM<sub>2.5</sub> levels alone increased CV mortality among infants, but were associated with decreased CV mortality among children, adolescents, and older adults. Interestingly, ambient PM<sub>2.5</sub> levels were negatively associated with CR mortality across all age groups. These patterns may be driven by the interplay between temperature and ambient PM<sub>2.5</sub> levels and by rural-urban differences, as reflected in the significant interaction terms observed across all age groups for both CV and CR mortality, which are the main focus of the next section.

Among sociodemographic controls, we found evidence that generally supports the SDH framework, with higher sociodemographic characteristics associated with lower CV and CR mortality across most age groups.

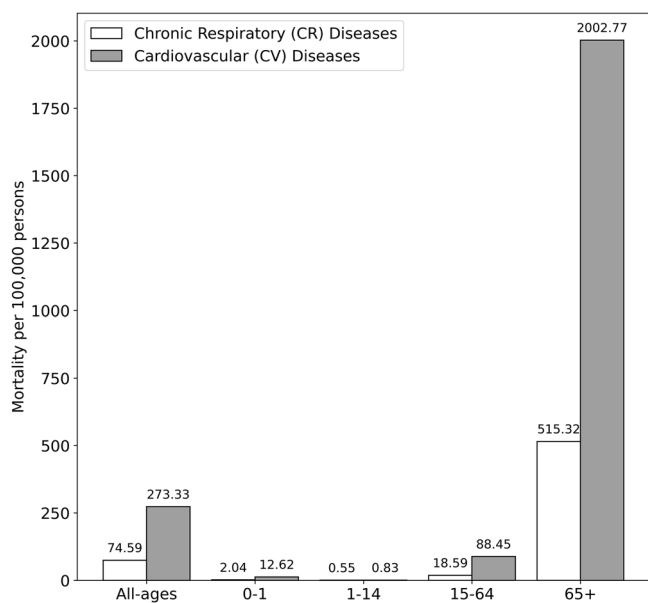
Specifically, higher household income and greater health insurance coverage were generally protective, reducing both CV and CR mortality in most age groups. Education was consistently associated with decreased mortality, regardless of cause of death or age group, suggesting that higher educational attainment, along with associated health literacy and healthier lifestyles, significantly reduces the risk of mortality. Poverty rate was significantly associated with lower CV and CR mortality only for infants, children, and

adolescents. This may be due to social welfare and health policies that prioritize these vulnerable populations in impoverished households.

### Cardiovascular diseases mortality

We further explored the impact of the interaction between temperature and ambient PM<sub>2.5</sub> on age-specific CV mortality in rural and urban counties (Fig. 2). The results suggest that ambient air pollution and temperature have heterogeneous impacts on cardiovascular disease mortality across the different age groups, with notable rural-urban disparities, including a rural mortality penalty for infants and a reduced mortality among working-age adults in rural counties. These results are shown with an air pollutant exposure below the air quality standard defined by the US Environmental Protection Agency<sup>45</sup>.

Specifically, we found that in most scenarios, higher temperatures were generally associated with increased CV mortality, and such effects were exacerbated by higher ambient fine PM readings in both rural and urban counties. However, the rural mortality penalty was only observed for the infant group, where mortality increased almost exponentially with higher ambient temperature in rural counties, with higher ambient PM<sub>2.5</sub> levels amplifying this effect, whereas in urban counties, this relationship is less pronounced. This finding suggests that infants in rural areas are particularly vulnerable to higher ambient temperatures and higher ambient fine PM levels. This pattern was likely driven by patients' limited access to healthcare facilities, such as specialized neonatal care and emergency medical services, and delayed medical interventions in rural areas. The working-age adult group presents a distinct pattern, showing a decreasing trend in mortality rates under similar environmental conditions. We found that mortality initially increases with higher ambient temperature in both rural and urban counties, but declines at higher temperature values in rural settings, particularly under higher ambient PM<sub>2.5</sub> levels. This pattern may reflect behavioral adaptations in rural areas, where residents may limit outdoor activities when temperatures rise and air quality deteriorates. In contrast, urban working-age populations experience a steady increase in mortality with increasing ambient temperature across all ambient PM<sub>2.5</sub> levels. This



**Fig. 1 | Cause- and age-specific mortality rates in the US, 2009–2019.** Mortality rates are measured as deaths per 100,000 persons across US counties ( $n = 3115$ ) for all ages and by age group (0–1, 1–14, 15–64, and 65+). Values above the bars indicate cause- and age-specific mortality rates.

**Table 1 | Descriptive statistics of environmental and sociodemographic factors across rural and urban counties in the US, 2009–2019**

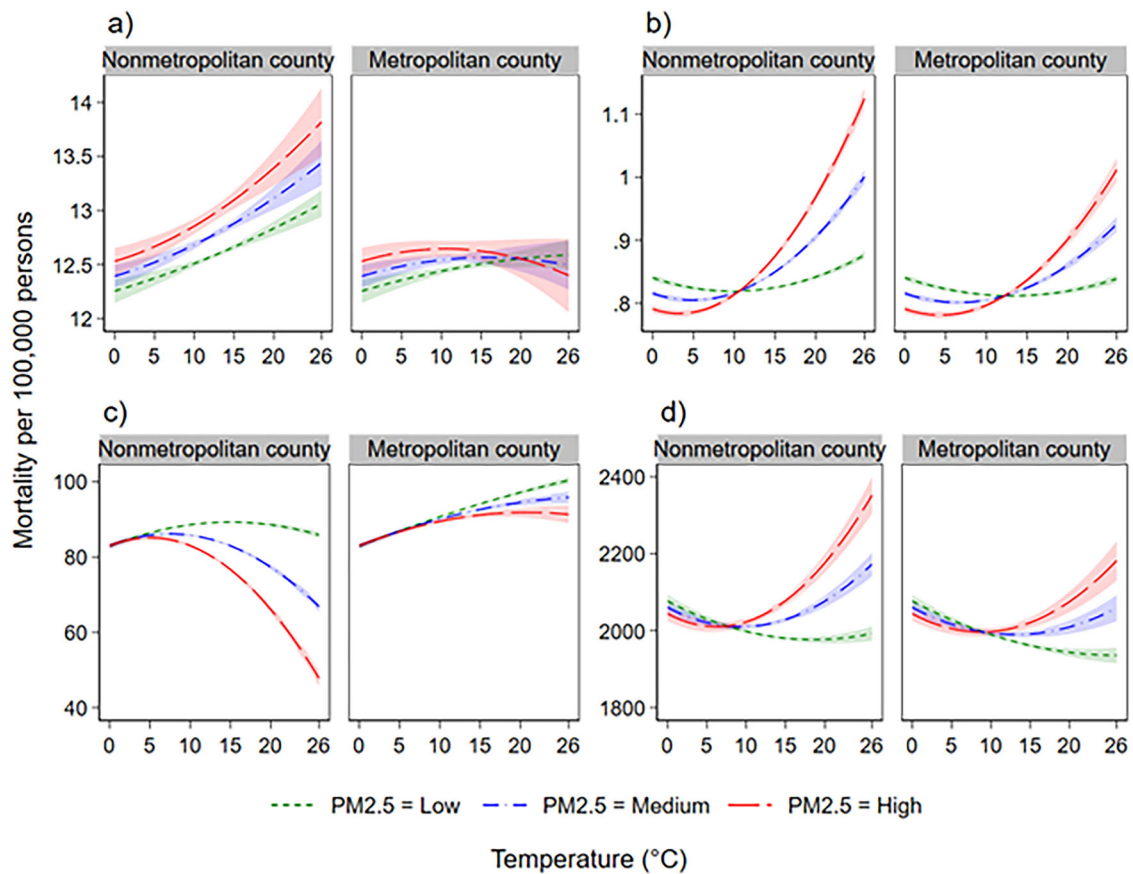
Variables	All counties ( $N = 34,199$ )	Rural counties ( $N = 21,428$ )	Urban counties ( $N = 12,771$ )	$p$ -value
CR mortality <sub>0-1</sub>	2.04	2.05	2.01	<0.001
CR mortality <sub>1-14</sub>	0.55	0.54	0.57	<0.001
CR mortality <sub>15-64</sub>	18.59	20.24	15.86	<0.001
CR mortality <sub>65+</sub>	515.32	550.42	457.04	<0.001
CV mortality <sub>0-1</sub>	12.62	12.75	12.39	<0.001
CV mortality <sub>1-14</sub>	0.83	0.82	0.84	<0.001
CV mortality <sub>15-64</sub>	88.45	93.36	80.29	<0.001
CV mortality <sub>65+</sub>	2002.77	2084.49	1867.77	<0.001
Temperature (°C)	12.75	12.19	13.68	<0.001
PM <sub>2.5</sub> (µg/m <sup>3</sup> )	7.34	7.05	7.84	<0.001
Household income	65.67	60.09	75.06	<0.001
% College graduate	49.95	47.16	54.63	<0.001
% Health insurance	85.30	84.49	86.65	<0.001
% Poverty	11.72	12.58	10.27	<0.001
Population size <sub>0-1</sub>	1253.25	271.22	2903.80	<0.001
Population size <sub>1-14</sub>	18,243.53	4065.05	42,074.13	<0.001
Population size <sub>15-64</sub>	67,375.59	14,936.94	1.6e + 05	<0.001
Population size <sub>65+</sub>	14,803.52	4157.84	32,696.34	<0.001
Metropolitan status	0.37	—	—	—

Values are means.  $p$ -values from two-sample  $t$ -tests are reported to compare rural and urban counties.  $N$  is the county-year pairs, with 3115 unique counties between 2009 and 2019. Mortality values are the number of deaths per 100,000 persons. Among the counties, 37% are metropolitan counties.

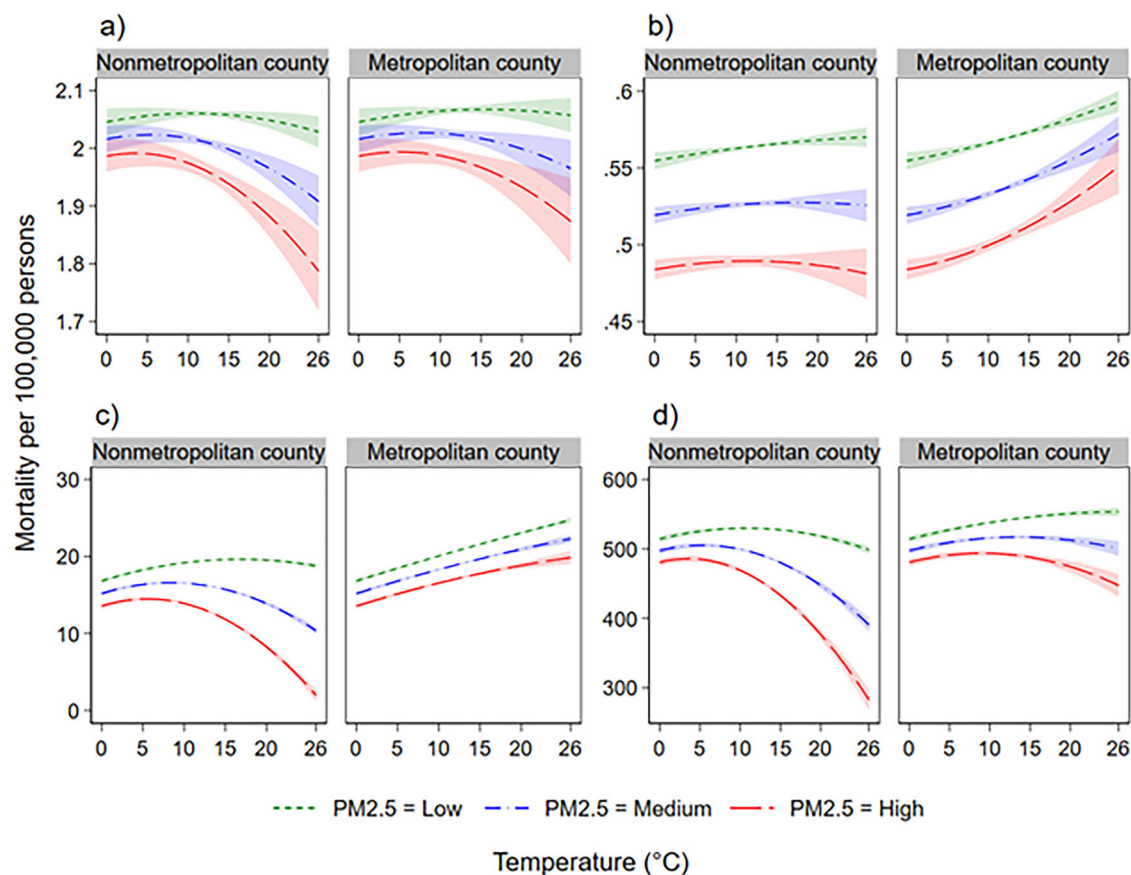
**Table 2 | Cause- and age-specific mortality models at the county level in the US, 2009–2019**

Variables	Cardiovascular mortality				Chronic respiratory mortality			
	0–1	1–14	15–64	65+	0–1	1–14	15–64	65+
Temperature	0.022***	-0.004***	0.848***	-10.807***	0.003**	0.001***	0.336***	2.907***
PM <sub>2.5</sub>	0.028***	-0.005***	0.011	-3.340***	-0.006***	-0.007***	-0.326***	-3.349***
Temperature <sup>2</sup> * PM <sub>2.5</sub> * Rural	7e-5**	4e-5***	-0.006***	0.058***	-3e-5***	-3e-6*	-0.002***	-0.027***
Temperature <sup>2</sup> * PM <sub>2.5</sub> * Urban	-7e-5**	3e-5***	-0.001***	0.041***	-2e-5***	4e-6***	-2e-4***	-0.011***
Household income	0.001	2e-4***	-0.059***	-0.758***	-5e-4**	-5e-4***	-0.039***	-0.398***
% College	-0.023***	-0.001***	-0.099***	-2.301***	-0.004***	-0.001***	-0.007*	-0.603***
% Health insurance	-0.004**	-3e-4***	0.117***	-2.824***	-3e-4	-2e-5	0.091***	-0.236***
% Poverty	-0.016***	-3e-4***	-0.012	0.340	-0.002***	-6e-5	2e-4	0.070
Age-specific population	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County effect	Omitted	Omitted	Omitted	Omitted	Omitted	Omitted	Omitted	Omitted
Constant	14.431***	0.994***	85.091***	2569.876***	2.303***	0.649***	14.625***	594.522***
Observations	33,830	33,830	33,830	33,830	33,830	33,830	33,830	33,830
R-squared	0.501	0.670	0.376	0.543	0.365	0.447	0.573	0.339
Number of counties	3076	3076	3076	3076	3076	3076	3076	3076
AIC	26,326	-170,918	157,458	365,233	-76,733	-173,706	88,751	287,824
BIC	26,494	-170,750	157,626	365,401	-76,564	-173,537	88,920	287,993

AIC Akaike's information criterion, BIC Schwartz's Bayesian information criterion.  
 \*\*\**p* < 0.001, \*\**p* < 0.01, \**p* < 0.05.



**Fig. 2 | The environmental impacts of ambient temperature and ambient fine PM on cardiovascular disease mortality rates are shown for the four age groups in rural and urban counties in the US, 2009–2019. a 0–1, b 1–14, c 15–64, and d 65+.** PM<sub>2.5</sub> category levels of 5, 15, and 20 µg/m<sup>3</sup> were used to represent low, medium, and high air pollution groups, respectively.



**Fig. 3 | The environmental impacts of ambient temperature and ambient fine PM on chronic respiratory disease mortality rates for the four age groups in rural and urban counties are shown in the US, 2009–2019. a 0–1, b 1–14, c 15–64, and d 65+.**

PM<sub>2.5</sub> category levels of 5, 15, and 20 µg/m<sup>3</sup> were used to represent low, medium, and high air pollution groups, respectively.

outcome is likely due to factors such as higher baseline ambient fine PM levels, urban heat island effects, and occupational stressors. The CV mortality of children, adolescents, and older adults showed similar patterns, with increases in mortality when ambient temperatures increased, particularly under higher ambient PM<sub>2.5</sub> levels of exposure. In both age groups, the effects were more pronounced in rural counties, where poor air quality and extreme heat may make existing health vulnerabilities worse.

**Chronic respiratory disease mortality**

Figure 3 shows the effects of the interaction between ambient temperature and ambient PM<sub>2.5</sub> on CR mortality across the four age groups in rural and urban counties. Higher temperatures generally increased CR mortality. However, unlike the CV mortality patterns, where decreasing mortality in rural counties only occurred for the working-age adults, CR mortality showed a significant rural paradox across all age groups, manifested in the following two patterns.

For the first mortality pattern, we found that infants and older adults shared similar CR mortality patterns under the influence of temperature and PM<sub>2.5</sub>, with both groups exhibiting an increase in CR mortality when temperatures increased, particularly when PM<sub>2.5</sub> levels were low. As PM<sub>2.5</sub> levels increased, mortality decreased among infants and older adults in both rural and urban counties, but rural counties experienced a sharper decrease compared to their urban counterparts. This unique pattern may represent behavioral adaptations and geographic differences between rural and urban counties. For example, older adults and infant caregivers may take more protective measures to reduce exposure by limiting the amount of time spent outdoors. Geographically, urban areas are subject to traffic-related air pollution, where pollutant components tend to be more hazardous than soil- and dust-related particles that are more common in rural settings,

contributing to higher CR mortality in urban areas. In contrast, rural areas may have greater access to open spaces and lower background ambient fine PM levels, which could mitigate the adverse effects of PM<sub>2.5</sub> compared to urban areas. To summarize, these results with the offered explanations suggest that while both age groups are highly vulnerable to temperature and air pollution stressors, behavioral adaptations and geographic differences provide some degree of protection for rural residents, by contributing to a downward trend in terms of environment-related CR mortality.

For the second mortality pattern, a rural mortality paradox was also observed for children, adolescents, and working-age adults, who share distinct mortality profiles from the mortality profile of infants and older adults. Specifically, while temperature and PM<sub>2.5</sub> still impact these groups, their effects tend to follow a downward trend as PM<sub>2.5</sub> levels rise, whereas in urban counties, the mortality rate increases monotonically with higher temperatures and increased PM<sub>2.5</sub> levels. As was mentioned previously, this rural paradox and urban penalty of CR mortality may be attributed to geographic and occupational differences between rural and urban settings. Rural areas generally have lower baseline pollution levels and greater access to green spaces, which may mitigate the adverse health effects of air pollution. In contrast, urban environments may increase health risks due to higher population density, built infrastructure, traffic congestion, industrial emissions, and the urban heat island effect, all of which exacerbate the adverse impact of heat and PM<sub>2.5</sub> exposure, leading to higher mortality. Occupational differences further contribute to the rural-urban disparity in CR mortality. Urban workers, particularly in industrial and manufacturing sectors, may face prolonged PM<sub>2.5</sub> exposure and are also susceptible to traffic-related pollution and heat stress, causing heightened mortality. Rural jobs and rural workers, on the other hand, may involve less exposure to high-pollution spaces, reducing prolonged inhalation of harmful

particulates. In sum, these findings suggest that while temperature and air pollution pose significant risks across all age groups, with geographic and occupational differences being expressed as a protective effect for rural residents and a penalty for urban residents regarding environment-related mortality.

## Discussion

Rapid environmental changes raise concern over their impact on population health. Among various environmental factors, warming temperatures and increasing air pollution are the two major drivers of health issues around the globe<sup>46,47</sup>. Previous studies have shown that high temperatures and air pollution are associated with cardiovascular and respiratory diseases and related deaths in both developing nations and developed countries<sup>25,47</sup>. However, the interaction between temperature and air quality and its influence on age- and cause-specific mortality has not been fully understood, especially in the US and other economically developed countries, where economy, infrastructure, and policy may demonstrate different relationships between environmental factors and population health than in economically developing countries. Utilizing age- and cause-specific mortality data, high-resolution climate data aggregated to county polygons, and the nationally representative American Community Survey data, we extended the SDH framework by incorporating environmental factors and explored the impact of temperature, air quality, and their interactions on age- and cause specific mortality at the county level in the US, with foci on age vulnerability and rural-urban disparities. We contributed a nuanced understanding of how environmental stressors, specifically temperature and air pollution, interact to influence age- and cause-specific mortality patterns in the US. Our results reveal complex rural-urban disparities that challenge the conventional rural mortality penalty narrative.

Our findings demonstrate that different age groups exhibit varying vulnerabilities to environment-related mortality, and the rural mortality penalty does not necessarily hold throughout all age groups and causes of death; the urban population may also face a penalty regarding environmental impacts on mortality. Specifically, we observed the following environment-related mortality patterns: First, we found that higher temperatures and poor air quality were generally associated with higher cardiovascular and respiratory deaths, a finding that is consistent with previous studies in both developing and developed settings<sup>47,48</sup>. This finding indicated that environmental changes such as extreme temperatures and higher ambient air pollution levels remain critical public health concerns, irrespective of the geographic or economic context.

Second, in line with the previously published literature, we observed a rural mortality penalty of cardiovascular diseases, particularly among infants under increasing ambient temperatures and heightened ambient air pollution levels<sup>34,37</sup>. This outcome suggested that rural populations, especially vulnerable groups such as infants, face multiple health risks due to a combination of environmental exposure and structural healthcare disadvantages that include limited access to neonatal care, emergency medical services, and timely interventions in rural America.

Third, in contrast to the rural disadvantages of cardiovascular deaths, we found lower respiratory mortality for children, working-age adults, and older adults in rural counties. Rural residents generally experienced lower respiratory mortality or a more rapid decline in mortality as temperatures and air pollution levels increased, compared to their urban counterparts. This observed rural mortality paradox can be attributed to lower baseline pollution exposure, better access to green spaces, and differences in occupational and behavioral factors, such as fewer industrial jobs and behavioral adaptation to reduce exposure.

Fourth, the urban penalty in respiratory mortality was found for children, adolescents, and working-age adults, and it occurred because of higher pollution, the urban heat island effect, and occupational exposure. Dense metropolitan infrastructures and the presence of heat-absorbing building materials intensify heat stress and worsen the effects of industrial and traffic emissions on overall air quality. Additionally, a significant proportion of urban jobs are in manufacturing, construction, and

transportation, exposing working-age adults to prolonged air pollution and heat-related risks and contributing to higher respiratory mortality in urban areas.

The findings are largely consistent with existing evidence on how the environment shapes health outcomes<sup>9</sup>. However, the rural paradox in respiratory disease-related deaths and the urban mortality penalty among working-age adults challenge the conventional narrative of environmental health disparities, underscoring the need for context-specific policy interventions. Addressing these disparities will require targeted strategies that consider infrastructural, occupational, and behavioral factors that shape the health outcomes in rural and urban settings on a broader scale. First, the rural mortality paradox in respiratory diseases highlights the protective role of early warning systems and greater access to green spaces. Policymaking, particularly in the economically developing world, could benefit from investing in early warning systems for extreme climate conditions, as well as expanding public awareness to promote behavioral adaptations that reduce exposure to harmful environmental conditions. Second, the urban mortality penalty among working-age adults demonstrates how geographic and occupational factors increase environmental health risks, even in economically developed countries. Reducing these risks in all countries requires targeted occupational health policies, environmental interventions, and urban planning strategies. Strengthening workplace regulations to mitigate heat and air pollution exposure is critical for protecting vulnerable workers. Additionally, expanding green infrastructure in urban areas, such as increasing tree canopy, building more urban parks, and using heat-reflective building materials, can also counteract the harmful effects of extreme temperatures, air pollution, and their reinforcing interactions.

The strengths of the study are twofold. First, we spatially integrated longitudinal mortality data from 2009 through 2019 with ambient temperature and air quality indicators to investigate environmental impacts on health. This strategy broadens the SDH framework and provides a more comprehensive picture of how both environmental and sociodemographic factors shape population health. Second, we examined heterogeneous environmental impacts on age- and cause-specific mortality across rural and urban counties in the US. These heterogeneous analyses offer a comprehensive assessment of not only the rural mortality penalty in CV-related deaths, but also a rural paradox in CR-related deaths, alongside an urban mortality penalty in CR-related deaths.

While this study is subject to two limitations, these shortcomings also highlight important opportunities for future research. A key limitation is the potential for scale effects arising from the aggregation of mortality data, environmental exposures, and sociodemographic characteristics at the county level, which may not apply to individuals and may mask important within-county heterogeneity in environmental exposures and health outcomes. Such aggregated analyses also make it difficult to establish causal relationships; therefore, the observed associations should be interpreted as correlations rather than causal relationships. Another limitation is that absolute mortality rates differ substantially across age groups, which necessitates a focus on within-age variation and constraints comparison across different age groups. Future research should further explore standardized approaches, such as relative risk scaling or age-standardized measurements, to facilitate more meaningful cross-age comparisons. In addition, studies leveraging finer spatial resolution data or individual-level health records linked with high-resolution environmental exposures can help reduce aggregation bias and provide insights into the mechanisms through which both environmental factors and sociodemographic characteristics shape health disparities across different demographic groups and places.

## Methods

### Data

The data for this study came from multiple sources (for more information, please refer to Table A1 in the Supplementary Information). The dependent variables were obtained from the Institute for Health Metrics and Evaluation<sup>49</sup>. This dataset included county-level cause-specific mortality

estimates for the US from 2000 through 2019. In this study, we focused on the period from 2009 to 2019 to align with the availability of county-level five-year estimates of sociodemographic factors, which became consistently available starting in 2009. This ensures that mortality and sociodemographic data were measured over comparable spatial and temporal scales, thereby allowing for a coherent linkage of all variables from different data files into one analyzable dataset. We did not include data after 2019 to avoid the confounding effects of the COVID-19 pandemic, during which time mortality patterns were highly skewed and may not reflect the typical associations between environmental exposures and health outcomes. Temperature readings come from the Parameter-elevation Regressions on Independent Slopes Model data, a commonly used downscaled high-resolution (0.04-degree resolution, approximately 4 km<sup>2</sup>) grid-level climate data product<sup>50,51</sup>. Validation studies between the model data and land-based weather station data suggested that it provides reliable estimates of weather conditions, particularly climate averages, with temperature and precipitation showing correlation coefficients greater than 0.95 and 0.65, respectively<sup>52,53</sup>. We used PM<sub>2.5</sub> to represent air quality. We obtained the model-generated ambient fine PM data from the Atmospheric Composition Analysis Group. Cross-validation using ground-based monitoring data demonstrated a high degree of accuracy, with reported correlation coefficient values exceeding 0.90<sup>54</sup>. County-level sociodemographic characteristics, including household income and education, come from the American Community Survey 5-year estimates, while the health insurance coverage data were sourced from the Small Area Health Insurance Estimates<sup>55</sup>. Regarding each county's rural-urban classification, we used the US Office of Management and Budget 2013 classification scheme to determine each county's metropolitan status and keep it consistent over time, since 2013 falls roughly in the middle of the 2009–2019 temporal interval, and is the only year in that time frame with the available rural-urban classification. We integrated these data to compile a county-level panel dataset spanning from 2009 through 2019 for this study.

## Variables

The dependent variables, county-level estimates of mortality, were categorized by cause of death and age groups, thereby allowing the investigation of heterogeneous environmental impacts on mortality across the utilized demographic groups. This dataset recorded 19 causes of death<sup>49</sup>. We selected death due to CV and CR diseases because they were among the major causes of death in the US<sup>44</sup> and are impacted by both environmental and societal pressures. For age-specific mortality analyses, we categorized the decedents into four groups: 0–1, 1–14, 15–64, and 65 and above, representing the mortality of infants, children and adolescents, working-age adults, and older adults, respectively.

For the environmental factors, we extracted annual mean temperature and PM<sub>2.5</sub> by averaging the values from the grid cells for each county (Fig. A1). The utilized aggregation method permitted attaining a consistent representation of environmental conditions at the county level and enabling their linkage to sociodemographic factors. By linking all files on the same spatial (county) and temporal (year) variables, it was then possible to analyze the mortality data within one merged master file that incorporated both the environmental and sociodemographic factors, all at the county level.

Based on the SDH framework and previous empirical evidence, income<sup>56,57</sup>, educational attainment<sup>4,5</sup>, poverty<sup>58,59</sup>, and health insurance<sup>7,60</sup> affect health outcomes such as mortality through behavioral<sup>61</sup> and physiological channels<sup>62</sup>. As such, we obtained those variables from the American Community Survey 5-year estimates and Small Area Health Insurance Estimates and included them in the analysis. Regarding county types, metropolitan counties are defined as those that (1) contain a core urbanized population of 50,000 or more persons or (2) are integrated with such core counties as measured by commuting zones, with the rest of the counties being classified as nonmetropolitan counties. Throughout the study, we used the terms metropolitan and urban, and nonmetropolitan and rural interchangeably.

## Statistical analysis

The primary objective was to explore the environmental impacts on cause- and age-specific mortality at the county level, controlling for socio-demographic characteristics known to influence mortality. Our specific objective was to evaluate the rural mortality penalty hypotheses and the intricate interplay between temperature and air quality in US counties. To this end, we estimated a series of models on the panel data from 2009 through 2019 to explore the heterogeneous environmental impacts of ambient temperature and ambient fine PM on cause-specific mortalities of infants, children and adolescents, working-age adults, and older adults. Each of the models followed the same general form:

$$Y_{i,t} = \beta_0 + \beta X_{i,t} + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (1)$$

where  $Y_{i,t}$  is the mortality of county  $i$  at time  $t$ ;  $\beta_0$  is the intercept;  $X_{i,t}$  is a matrix of environmental and sociodemographic factors;  $\beta$  is the estimated coefficient;  $\gamma_i$  and  $\delta_t$  are entity (i.e., county) and time (i.e., year) fixed-effects, accounting for unobserved effects such as food and nutrient supply, infrastructure, and health policy that will influence mortality;  $\varepsilon_{i,t}$  is the error term. Given that age-specific mortality rates depend on the population size of each age group, we included the age-specific population of each county in the models. Additionally, temperature may have nonlinear effects on health and could interact with PM<sub>2.5</sub> differently across rural and urban counties. To account for these complexities, we included interaction terms between the squared term of temperature and PM<sub>2.5</sub>, as well as rural-urban status. This specification allowed us to assess the environmental impacts of both ambient temperature and ambient fine PM on cause- and age-specific mortality in diverse county-specific conditions.

## Data availability

The data used in this study are listed in Table A1 and are publicly available. The analyses in this study were conducted using Python and Stata, and the corresponding data and code are available in the following GitHub repository: <https://github.com/shuai-zhou/EnvMortality>.

## Code availability

The analyses in this study were conducted using Python and Stata, and the corresponding code is available in the following GitHub repository: <https://github.com/shuai-zhou/EnvMortality>.

Received: 11 April 2025; Accepted: 22 December 2025;

Published online: 04 May 2026

## References

- Hood, C. M., Gennuso, K. P., Swain, G. R. & Catlin, B. B. County health rankings: relationships between determinant factors and health outcomes. *Am. J. Prev. Med.* **50**, 129–135 (2016).
- Holt-Lunstad, J. Social connection as a public health issue: the evidence and a systemic framework for prioritizing the quot social quot in social determinants of health. *Annu. Rev. Public Health* **43**, 193–213 (2022).
- Donkin, A., Goldblatt, P., Allen, J., Nathanson, V. & Marmot, M. Global action on the social determinants of health. *BMJ Glob. Heal.* **3**, e000603 (2017).
- Brown, D. C. et al. The significance of education for mortality compression in the United States. *Demography* **49**, 819–840 (2012).
- Buckles, K., Hagemann, A., Malamud, O., Morrill, M. & Wozniak, A. The effect of college education on mortality. *J. Health Econ.* **50**, 99–114 (2016).
- O'Brien, R., Bair, E. F. & Venkataramani, A. S. Death by Robots? Automation and working-age mortality in the United States. *Demography* **59**, 607–628 (2022).
- Goldin, J., Lurie, I. Z. & McCubbin, J. Health insurance and mortality: Experimental evidence from taxpayer outreach. *Q. J. Econ.* **136**, 1–49 (2021).

8. Chetty, R. et al. The association between income and life expectancy in the United States, 2001–2014. *JAMA* **315**, 1750–1766 (2016).
9. Vicedo-Cabrera, A. M. et al. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Chang.* **11**, 492–500 (2021).
10. Jian, Y. et al. Associations between environmental quality and infant mortality in the United States, 2000–2005. *Environ. Health Perspect.* **125**, 355–362 (2017).
11. Kephart, J. L. et al. City-level impact of extreme temperatures and mortality in Latin America. *Nat. Med.* **28**, 1700–1705 (2022).
12. Ye, T. et al. Short-term exposure to wildfire-related PM<sub>2.5</sub> increases mortality risks and burdens in Brazil. *Nat. Commun.* **13**, 1–9 (2022).
13. Raaschou-Nielsen, O. et al. PM<sub>2.5</sub> air pollution components and mortality in Denmark. *Environ. Int.* **171**, 107685 (2023).
14. Sun, Y. et al. Impact of Heavy PM<sub>2.5</sub> Pollution Events on Mortality in 250 Chinese Counties. *Environ. Sci. Technol.* **56**, 8299–8307 (2022).
15. Jin, T. et al. Associations between long-term exposures to airborne PM<sub>2.5</sub> components and mortality in Massachusetts: mixture analysis exploration. *Environ. Health* **21**, 96 (2022).
16. Richmond-Bryant, J., Mikati, I., Benson, A. F., Luben, T. J. & Sacks, J. D. Disparities in distribution of particulate matter emissions from US coal-fired power plants by race and poverty status after accounting for reductions in operations between 2015 and 2017. *Am. J. Public Health* **110**, 655–661 (2020).
17. Eisenberg, J. N. S. et al. Environmental determinants of infectious disease: A framework for tracking causal links and guiding public health research. *Environ. Health Perspect.* **115**, 1216–1223 (2007).
18. Sogno, P., Kuenzer, C., Bachofer, F. & Traidl-Hoffmann, C. Earth observation for exposome mapping of Germany: analyzing environmental factors relevant to non-communicable diseases. *Int. J. Appl. Earth Obs. Geoinf.* **114**, 103084 (2022).
19. Lamboll, R. D. et al. Assessing the size and uncertainty of remaining carbon budgets. *Nat. Clim. Chang.* **13**, 1360–1367 (2023).
20. Wild, C. P. Complementing the genome with an ‘exposome’: The outstanding challenge of environmental exposure measurement in molecular epidemiology. *Cancer Epidemiol. Biomark. Prev.* **14**, 1847–1850 (2005).
21. Wild, C. P. The exposome: From concept to utility. *Int. J. Epidemiol.* **41**, 24–32 (2012).
22. Cui, Y. et al. The exposome: embracing the complexity for discovery in environmental health. *Environ. Health Perspect.* **124**, A137–A140 (2016).
23. Davis, R. E., Knappenberger, P. C., Michaels, P. J. & Novicoff, W. M. Changing heat-related mortality in the United States. *Environ. Health Perspect.* **111**, 1712–1718 (2003).
24. Guo, Y. et al. Heat wave and mortality: A multicountry, multicomunity study. *Environ. Health Perspect.* **125**, 1–11 (2017).
25. Hajat, S. & Kosatky, T. Heat-related mortality: A review and exploration of heterogeneity. *J. Epidemiol. Community Health* **64**, 753–760 (2010).
26. Carugno, M., Consonni, D., Bertazzi, P. A., Biggeri, A. & Baccini, M. Temporal trends of PM<sub>10</sub> and its impact on mortality in Lombardy, Italy. *Environ. Pollut.* **227**, 280–286 (2017).
27. Willers, S. M. et al. High resolution exposure modelling of heat and air pollution and the impact on mortality. *Environ. Int.* **89–90**, 102–109 (2016).
28. Schraufnagel, D. E. The health effects of ultrafine particles. *Exp. Mol. Med.* **52**, 311–317 (2020).
29. Kang, Y. J., Tan, H. Y., Lee, C. Y. & Cho, H. An Air Particulate Pollutant Induces Neuroinflammation and Neurodegeneration in Human Brain Models. *Adv. Sci.* **8**, e2101251 (2021).
30. Woodruff, T. J., Parker, J. D. & Schoendorf, K. C. Fine particulate matter (PM<sub>2.5</sub>) air pollution and selected causes of postneonatal infant mortality in California. *Environ. Health Perspect.* **114**, 786–790 (2006).
31. Perera, F. & Nadeau, K. Climate Change, Fossil-Fuel Pollution, and Children’s Health. *N. Engl. J. Med.* **386**, 2303–2314 (2022).
32. Rau, A. et al. Nationwide assessment of ambient monthly fine particulate matter (PM<sub>2.5</sub>) and its associations with total, cardiovascular and respiratory mortality in the United States. *Environ. Res. Heal.* **1**, 025001 (2023).
33. Kazemiparkouhi, F. et al. The impact of Long-Term PM<sub>2.5</sub> constituents and their sources on specific causes of death in a US Medicare cohort. *Environ. Int.* **159**, 106988 (2022).
34. Rhubarb, D. & Santos, A. Research Note Showing That the Rural Mortality Penalty Varies by Region, Race, and Ethnicity in the United States, 1999–2016. *Demography* **60**, 1699–1709 (2023).
35. James, W. L. All rural places are not created equal: Revisiting the rural mortality penalty in the United States. *Am. J. Public Health* **104**, 2122–2129 (2014).
36. Miller, C. E. & Vasan, R. S. The southern rural health and mortality penalty: A review of regional health inequities in the United States. *Soc. Sci. Med.* **268**, 113443 (2021).
37. Cosby, A. G. et al. Growth and persistence of place-based mortality in the United States: The rural mortality penalty. *Am. J. Public Health* **109**, 155–162 (2019).
38. Cleland, S. E., Steinhardt, W., Neas, L. M., Jason West, J. & Rappold, A. G. Urban heat island impacts on heat-related cardiovascular morbidity: A time series analysis of older adults in US metropolitan areas. *Environ. Int.* **178**, 108005 (2023).
39. Lowe, S. A. An energy and mortality impact assessment of the urban heat island in the US. *Environ. Impact Assess. Rev.* **56**, 139–144 (2016).
40. Bell, M. L. & Ebisu, K. Environmental inequality in exposures to airborne particulate matter components in the United States. *Environ. Health Perspect.* **120**, 1699–1704 (2012).
41. Berberian, A. G., Gonzalez, D. J. X. & Cushing, L. J. Racial Disparities in Climate Change-Related Health Effects in the United States. *Curr. Environ. Heal. Rep.* **9**, 451–464 (2022).
42. Howarth, M. V. & Eiser, A. R. Environmentally Mediated Health Disparities. *Am. J. Med.* **136**, 518–522 (2023).
43. Kochanek, K. D., Murphy, S. L., Xu, J. & Arias, E. *Mortality in the United States, 2022. NCHS Data Brief* <https://doi.org/10.15620/cdc:135850> (2024)
44. Ahmad, F. B. & Anderson, R. N. The leading causes of death in the US for 2020. *JAMA* **325**, 1829–1830 (2021).
45. Jbaily, A. et al. Air pollution exposure disparities across US population and income groups. *Nature* **601**, 228–233 (2022).
46. Bell, M. L., Gasparini, A. & Benjamin, G. C. Climate change, extreme heat, and health. *N. Engl. J. Med.* **390**, 1793–1801 (2024).
47. Kazi, D. S. et al. Climate change and cardiovascular health: a systematic review. *JAMA Cardiol.* **9**, 748–757 (2024).
48. Andersen, Z. J., Vicedo-Cabrera, A. M., Hoffmann, B. & Melén, E. Climate change and respiratory disease: clinical guidance for healthcare professionals. *Breathe* **19**, 220222 (2023).
49. Dwyer-Lindgren, L. Cause-specific mortality by county, race, and ethnicity in the USA, 2000–19: a systematic analysis of health disparities. *Lancet* [https://doi.org/10.1016/S0140-6736\(23\)01088-7](https://doi.org/10.1016/S0140-6736(23)01088-7) (2023).
50. Daly, C. et al. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *Int. J. Climatol.* **28**, 2031–2064 (2008).
51. Dudley, J. et al. Nonlinear shifts in infectious rust disease due to climate change. *Nat. Commun.* **12**, 1–13 (2021).
52. Behnke, R. et al. Evaluation of downscaled, gridded climate data for the conterminous United States. *Ecol. Appl.* **26**, 1338–1351 (2016).
53. Spangler, K. R., Weinberger, K. R. & Wellenius, G. A. Suitability of gridded climate datasets for use in environmental epidemiology. *J. Expo. Sci. Environ. Epidemiol.* **29**, 777–789 (2019).

54. Van Donkelaar, A. et al. Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty. *Environ. Sci. Technol.* **55**, 15287–15300 (2021).
55. US Census Bureau. 2008 - 2021 Small Area Health Insurance Estimates (SAHIE) using the American Community Survey (ACS). <https://www.census.gov/data/datasets/time-series/demo/sahie/estimates-ac.html> (2023).
56. Kondo, N. et al. Income inequality, mortality, and self-rated health: Meta-analysis of multilevel studies. *BMJ* **339**, b4471 (2009).
57. Snyder, S. E. & Evans, W. N. The effects of income on mental health: Evidence from the social security notch. *Rev. Econ. Stat.* **88**, 482–495 (2006).
58. Gordon, S. H. & Sommers, B. D. Recessions, Poverty, and Mortality in the United States. *Am. J. Heal. Econ.* **2**, 489–510 (2016).
59. Brady, D., Kohler, U. & Zheng, H. Novel estimates of mortality associated with poverty in the US. *JAMA Intern. Med.* **183**, 618–619 (2023).
60. Gong, G., Phillips, S. G., Hudson, C., Curti, D. & Philips, B. U. Higher us rural mortality rates linked to socioeconomic status, physician shortages, and lack of health insurance. *Health Aff.* **38**, 2003–2010 (2019).
61. Braveman, P. & Gottlieb, L. The social determinants of health: It's time to consider the causes of the causes. *Public Health Rep.* **129**, 19–31 (2014).
62. Samuels, L. et al. Physiological mechanisms of the impact of heat during pregnancy and the clinical implications: review of the evidence from an expert group meeting. *Int. J. Biometeorol.* **66**, 1505–1513 (2022).

### Acknowledgements

We appreciate the constructive feedback from two anonymous reviewers. We acknowledge funding from the Cornell Center for Social Sciences and the Cornell Center for Health Equity.

### Author contributions

S.Z., C.L., and Z.W. designed the research; S.Z. performed research and wrote the manuscript; G.C. edited the manuscript. All authors reviewed and revised the manuscript.

### Competing interests

The authors declare no competing interests.

### Additional information

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s44432-025-00005-x>.

**Correspondence** and requests for materials should be addressed to Chuan Liao.

**Reprints and permissions information** is available at <http://www.nature.com/reprints>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026