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Spatial patterns of environmental injustice in social vulnerability and ambient dust levels across Australia

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2 **Spatial patterns of environmental injustice in social vulnerability and ambient dust levels**
3 **across Australia**
4

5 Sylvester Dodzi Nyadanu ^{a,b*}, Massimo Vieno ^c, Siqin Wang ^{d,e,f}, Gizachew A. Tessema ^{a,g,h}, Gavin
6 Pereira ^{a,g,i}
7

8
9 ^aCurtin School of Population Health, Curtin University, Perth, Western Australia 6102, Australia

10 ^bHealthy Environments and Lives (HEAL) National Research Network, Australia

11 ^cUK Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, UK

12 ^dSpatial Sciences Institute, Dornsife College of Letters, Arts and Sciences, University of Southern
13 California, Los Angeles, California, USA.

14 ^eSchool of Science, RMIT University, Melbourne, Victoria, Australia.

15 ^fSchool of Earth and Environmental Sciences, University of Queensland, Brisbane, Australia

16 ^genAble Institute, Curtin University, Perth, Kent Street, Bentley, Western Australia 6102, Australia

17 ^hSchool of Public Health, University of Adelaide, Adelaide, South Australia, Australia

18 ⁱWHO Collaborating Centre for Climate Change and Health Impact Assessment, Faculty of Health
19 Science, Curtin University, Bentley, WA, Australia
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22
23 *Correspondence: sylvester.nyadanu@curtin.edu.au (SDN)
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Abstract

Introduction: Ambient dust exposure has been associated with several adverse health outcomes. Unlike ambient air pollution, the vulnerability of subpopulations to ambient dust has not yet been explored. As the driest inhabited continent, Australia provides a natural laboratory for studying large-scale dust exposure. This study aimed to examine environmental injustice in ambient dust of $\leq 10 \mu\text{m}$ particle size and vulnerability of subpopulations in Australia, which has not been studied previously.

Methods: A nationwide cross-sectional design was employed by linking a highly spatially resolved census-derived composite measure of social vulnerability index (a wide range of factors measuring susceptibility, and a more complex capacity of individuals and society to cope with hazards and damage) to 2021 annual mean ambient dust concentrations in Australia. Local spatial autocorrelations, bivariate spatial correlations, and generalised additive logistic regression with spatial smoothing were applied to investigate geographic variation and the association between social vulnerability and ambient dust at the Australian Census' most precise geographical unit.

Results: The results indicated geographical inequalities of social vulnerability and ambient dust exposure, with a positive association and more elevated in urban areas than in rural areas. Those with high vulnerability were 13% more likely to reside in areas with the highest dust exposure (OR 1.13, 95% CI: 1.03, 1.23). High dust exposure was especially elevated in urban areas (OR 1.74, 95% CI: 1.42, 2.13) and areas with relatively high cultural and minority vulnerability (OR 3.55, 95% CI: 3.20, 3.94) and housing vulnerability (OR 2.63, 95% CI: 2.38, 2.90).

Conclusion: Social vulnerability is associated with greater exposure to ambient dust with identified hotspots, particularly in urban areas and communities with elevated cultural and housing vulnerability. These areas could be prioritised for policies and interventions to reduce the health burden of ambient dust, as initial steps to addressing environmental injustice in Australia.

Keywords: Dust; particulate matter air pollution; vulnerability; climate change; environmental justice

1. Introduction

Dust is present in our environment, including homes, workplaces, communities and public spaces, exposing everyone to at least some level of dust. Dust consists of solid particles ranging in size from less than 1 μm to hundreds of microns in size, released into the air from both natural and anthropogenic sources¹. Natural sources include soil and sand, sea salt, wildfire smoke, natural disasters, pollen, and spores. Anthropogenic sources include construction, industrial, mining, transportation, and agricultural activities^{1,2}. Ambient dust can remain in the atmosphere for hours to weeks and travel great distances from its sources, depending on particle size and meteorological conditions. Ambient dust is a major contributor to high concentrations of harmful particulate matter air pollution with sizes up to 2.5 μm (PM_{2.5}) and 10 μm (PM₁₀)¹⁻³. Although there is no biologically tolerated dose, the 2021 World Health Organization air quality guidelines recommend annual concentrations for PM_{2.5} and PM₁₀ at $\leq 5 \mu\text{g}/\text{m}^3$ and $\leq 15 \mu\text{g}/\text{m}^3$, respectively, to minimise the harmful effects of these toxic pollutants⁴.

Ambient dust has been associated with several health outcomes, such as all-cause cardiovascular and respiratory mortality and morbidity^{2,5,6} and exacerbation of infectious disease outbreaks⁷. Ambient dust can adversely affect health through well-documented pathways, such as airway irritation, oxidative stress, systemic inflammation, and impaired immune, respiratory and cardiovascular functions⁵⁻⁷. In the context of climate change, which exacerbates dust emissions and health risks, these impacts may be more concerning for socioeconomically and geographically vulnerable subpopulations, particularly vulnerable groups with weaker immune systems^{1,2,8}. Vulnerability, whether biophysical or social, broadly refers to individuals and populations at greater risk of health outcomes or environmental impacts⁹. Biophysical vulnerability relates to the likelihood of experiencing the impact of environmental exposures due to an individual's biological or physiological conditions, while social vulnerability encompasses the social or geodemographic characteristics of a population, such as age, gender, ethnicity, disability, geographic location, urban-rural disparity, infrastructural and healthcare access, housing, and socioeconomic disadvantage^{9,10}. Since human societies are integrated into complex social-ecological systems, social vulnerability is conceptualised into two dimensions: sensitivity to environmental hazards and the capacity to cope with their effects¹¹. From an environmental justice perspective, since the early 1970s, inequalities in environmental exposures (e.g., air pollution or dust exposure) are often driven by disparities in social structure and resource distribution^{9,11-13}. Dust exposure inequalities have reflected the same historical structural inequities central to the environmental justice framework. These inequities are driven by policy decisions, such as residential segregation, discriminatory lending, exclusionary zoning, and siting industrial and transport infrastructure¹²⁻¹⁴. These social structural processes systematically placed racially/ethnically and socioeconomically marginalised communities closer to major anthropogenic dust sources such as construction, industrial land uses, and agriculture, creating persistent inequities in exposure¹²⁻¹⁴. Natural dust provides a broad baseline, but human activity amplifies risks, and anthropogenic sources cluster in marginalised neighbourhoods due to the structural inequities. These communities face disproportionate risks, with environmental justice frameworks highlighting why marginalised groups face higher risks^{3,12-15}. Thus, the mechanism of action is both biological and social stratification, where ambient dust acts as both a pollutant and a proxy for systemic inequality^{12-14,16}.

Emerging literature has demonstrated positive associations between the spatial distribution of ambient air pollution and social vulnerability or vulnerable subpopulations in both high and low-income countries^{9,11,17-21}. However, to the best of our knowledge, no study has specifically investigated ambient dust exposure in relation to social vulnerability. As the driest inhabited continent and a major source of dust, Australia has been described as a natural laboratory for studying large-scale dust, its sources, transport, and geochemical composition²² with dust activity varying by a factor of four on decadal timescales²³. Australia regularly experiences dust storms that impact agriculture, health, and the economy, especially during droughts and periods of low vegetation. For example, the February 2019 inland dust storm event in New South Wales (the most populous state in Australia) resulted in

1
2 increased air pollution and respiratory hospitalisations and greater than concurrent bushfire events²⁴.
3 Bushfires and dust storms were identified as primary sources of PM_{2.5} from 2001–2019, with the
4 greatest concentration and health impacts reported in the Northern Territory and among men across all
5 regions²⁵. High agricultural dust exposure was also reported among rural workers in Western Australia
6 during harvest²⁶. A few Australian studies reported disproportionate ambient air pollution exposure
7 (PM_{2.5}, NO₂, and industrial emissions) among lower-income, Indigenous, and ethnic minority
8 communities, especially in urban and industrial areas^{19,27,28}. However, ambient dust exposure
9 specifically and hotspot areas remained unexamined, leaving a critical gap in Australia's
10 environmental justice literature. Understanding continental-level spatial inequalities in ambient dust
11 exposure and social vulnerability is important to inform policy responses, especially given the potential
12 long-term health impacts on vulnerable subpopulations^{2,5,6}. Therefore, this study aimed to use a
13 nationwide novel social vulnerability index (SVI)¹⁰ and a novel assessment of ambient dust exposure
14²⁹ to examine whether socially vulnerable populations in Australia face higher dust exposure overall
15 and in urban and rural areas. We hypothesised that environmental injustice and structural factors
16 amplify exposure inequalities.
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20 **2. Methods**

21 *2.1 Study area*

22 Australia is a continent that covers 7.7 million km² as the sixth-largest country in the world by area
23 coverage and a population of 25.4 million according to the 2021 census. Australia is highly urbanised,
24 with almost 80% of the population living in cities of the eight states/territories. As a culturally and
25 linguistically diverse country, about 52% of Australian residents were born overseas (29%) or have at
26 least one parent born overseas (22%)³⁰. The economy of Australia by the recent Human Development
27 Index (HDI) ranked 5th in the world in 2021³¹. The country also has extremely variable geology,
28 geochemistry, geomorphological settings, and climatic conditions with a large part in arid to semi-arid
29 zones defined by little rainfall²². The main geographical classification of Australia, as defined by the
30 Australian Bureau of Statistics (ABS), divides Australia into a hierarchy of statistical areas for
31 reporting a broad range of social, demographic, and economic statistics³². This comprises six states
32 and two mainland territories, local government areas, Statistical Area Levels 4 to 1 (SA4 to SA1), and
33 mesh blocks (the smallest geographic areas that form the building blocks for the larger regions). SA1s
34 are the second smallest geographical units which generally have a population of 200 to 800 people,
35 and an average of about 400 people – the smallest units in which sensitive census data are released to
36 maintain confidentiality³². This study used SA1s as spatial units of analysis (Figure 1).
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42 *2.2 Social vulnerability index (SVI) measurement*

43 We used the nationwide fine-grained measures of SVI data at SA1 spatial units described in Wang *et al*
44¹⁰. The SVI is an evenly weighted arithmetic (additive) aggregated index derived through a principal
45 composite index of 41 indicators for five themes from the ABS census data and many other data
46 sources. The five themes were Socioeconomic vulnerability, Demographics/Disability vulnerability,
47 Minority and Languages/Cultural vulnerability, Housing vulnerability, and Built
48 environment/Infrastructural vulnerability. The indicators for each theme were summarised in Table
49 S1. Out of the 57,523 SA1s in the 2016 census, the index for each theme, the overall SVI, and
50 remoteness (urban and rural) were generated for 55,218 SA1s. The remaining SA1s, with populations
51 of fewer than 50, were excluded as the ABS randomly assigned their populations for data privacy
52 purposes¹⁰. For SVI overall and within each theme, a higher vulnerability score indicates a greater
53 degree of vulnerability. The SVI and the themes capture structural and social processes in line with the
54 environmental justice framework.
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58 The novel SVI supplements the traditional socio-economic indexes for areas (SEIFA) derived from
59 census data by ABS³³ by additionally including features of housing, transport, and the built
60 environment that are only partially included in SEIFA. The SVI further innovatively reformed Cutter's

framework³⁴ to involve four-dimensional quantification of the built environment: diversity, design, density, and distance¹⁰. Comprehensive descriptions of the data sources, principal component analyses procedures in constructing the SVI, and the validation and sensitivity analyses were described in Wang *et al*¹⁰.

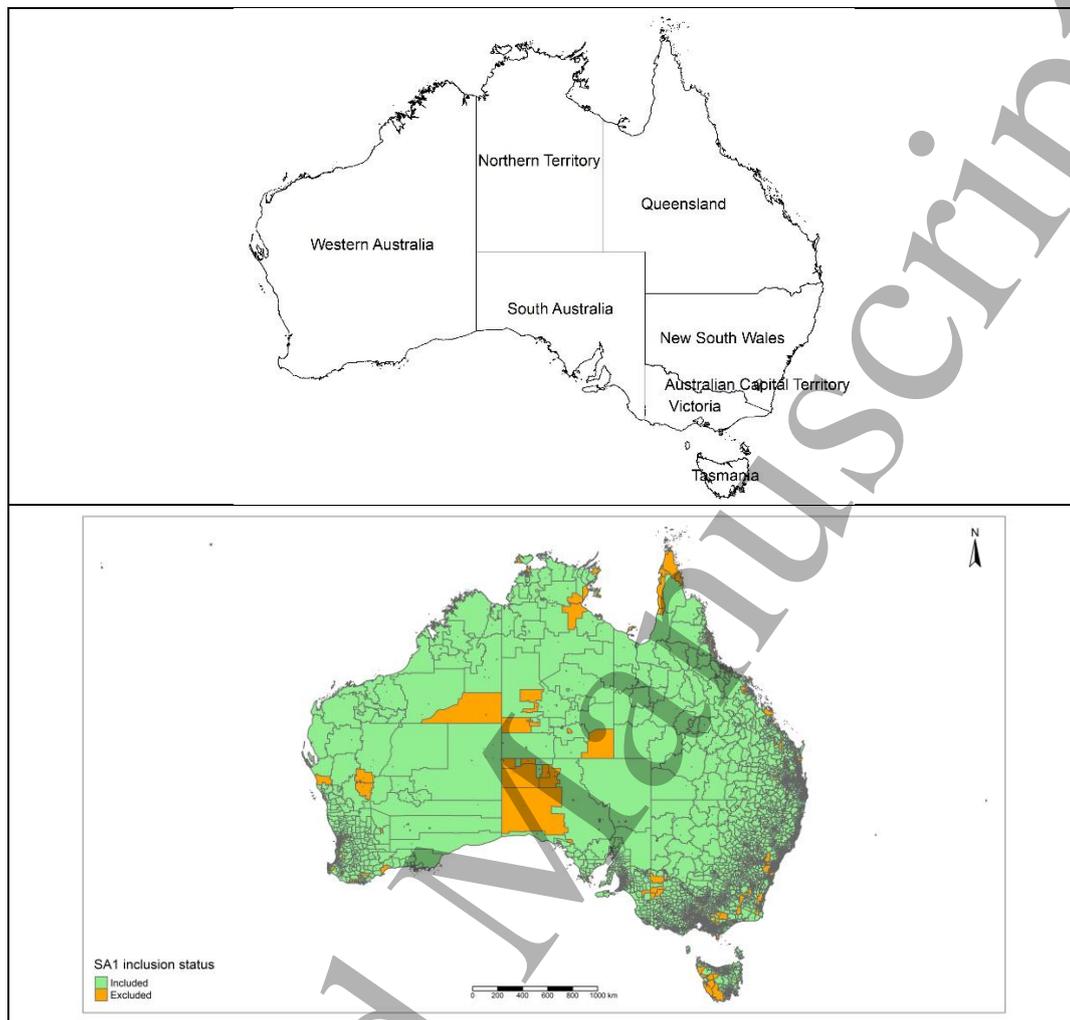


Figure 1. Map of Australia showing states/territories and the included SA1 in green (N = 55,177) and excluded SA1 in orange (N = 2,346) using the 2016 Australian Statistical Geography Standard shapefile (Available at <https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001.July%202016>) Note: The Excluded SA1s from the analysis were SA1s with populations of fewer than 50 people randomly assigned by Australian Bureau of Statistics due to the concern of data privacy or SA1s with missing

2.3 Ambient dust exposure assessment

This study used ambient dust (mainly wind-brown mineral) particles within the PM₁₀ size from the new assessment of global and regional budgets, fluxes, and lifetimes of atmospheric reactive species and aerosols²⁹. Briefly, the EMEP MSC-W (European Monitoring and Evaluation Programme Meteorological Synthesising Centre –West) open-source atmospheric chemistry transport model version 4.45 was coupled with the WRF (Weather Research and Forecasting) model version 4.2.2³⁵ meteorology to undertake a global and regional quantification of the concentrations, deposition, budgets, and lifetimes of atmospheric reactive species and aerosols^{29,36,37}. The WRF underline meteorology is the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate (ERA5)³⁸. The EMEP MSC-W calculates the 3D hourly concentration of pollutants that are then averaged to the annual mean. This included the near-surface concentration of mineral dust to 3m above the surface. The EMEP MSC-W model calculation was performed using the 2021 meteorological year, with the anthropogenic emissions derived from the EDGAR v6 2018 emissions inventories³⁹. Ambient dust is generated

1
2 online in the model and directly linked with the specific meteorological conditions. The EMEP MSC-
3 W model uses two nested domains: a global domain with a resolution of 1x1 degrees and a nested
4 domain covering Australia at a horizontal resolution of 0.11x0.11 degrees. This study used the 2021
5 annual average ambient mineral dust concentration ($\mu\text{g m}^{-3}$) across Australia at a spatial resolution of
6 ~ 10 km (0.11x0.11 degrees)²⁹. We note that dust concentrations can fluctuate substantially within a
7 year, with short-term spikes during dust storms that were not fully captured by the annual average.
8 With the 2016 boundary files (used for the SVI) from the Australian Statistical Geography Standard,
9 defined by the ABS⁴⁰, the mean ambient dust concentration at SA1 levels across Australia was
10 obtained using ArcGIS ArcMap software (version 10.8.1) and the R package *terra*. The SVI and
11 ambient dust concentration datasets were merged, and 41 SAs with missing dust concentrations were
12 excluded. The final analytical sample size was 55,177 SA1s with a total population of 23,331,456
13 persons (Figure 1).
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16 2.4 Statistical analyses

17 We employed a five-step methodology for exploratory non-spatial and spatial data analyses and
18 estimated the spatial association between SVI and ambient dust exposure. The main analyses and geo-
19 visualisations were performed using R software (version 4.3.3) with packages ‘tmap’, ‘spdep’, ‘mgcv’,
20 and ‘forestploter’.
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23 i. Descriptive statistics and choropleth mapping of SVI and ambient dust

24 Summary statistics were performed to report mean, standard deviations, medians, range, and
25 interquartile range for continuous forms and frequencies and percentages for categorical forms of the
26 ambient dust exposure, SVI, and the individual themes of SVI. SVI and ambient dust distributions
27 were mapped.
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30 ii. Univariate global spatial autocorrelation to determine spatial clustering or dispersion

31 The commonly used metric of spatial autocorrelation, univariate global Moran’s I (a cross-product
32 statistic between a variable and its spatial lag), was used to measure the degree of spatial clustering or
33 dispersion in the geographical distribution of the ambient dust and SVI across the study area. Moran’s
34 I range from +1 (spatial clustering) to -1 (spatial dispersion)^{41,42}.
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37 iii. Univariate local indicator of spatial association to identify cluster-outlier locations

38 A univariate local Moran’s I as a local indicator of spatial association (LISA) was performed
39 to determine the spatial cluster-outlier locations of the ambient dust and SVI. Local Moran’s I allowed
40 for the decomposition of global Moran’s I into the contribution of each location to identify locations
41 with clustering of *high-high* values (hotspots) which are high ambient dust or SVI areas surrounded
42 by other areas with high values and *low-low* values (coldspots) as areas with low ambient dust or SVI
43 surrounded by other areas with low values of low ambient dust or SVI. Outliers were also detected as
44 *high-low* and *low-high* values for areas with high and low ambient dust or SVI surrounded by other
45 areas with low and high values, respectively^{43,44}.
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48 iv. Bivariate Pearson and spatial Lee statistics correlation.

49 Pearson and Lee’s statistics were performed to determine non-spatial and spatial correlations between
50 ambient dust and SVI, respectively. Lee’s L statistics is a bivariate association measure that integrates
51 non-spatial bivariate association (Pearson correlation) with a univariate spatial association measure
52 (Moran’s I) between ambient dust and SVI⁴⁵. Bivariate local spatial associations were also performed.
53 Unlike bivariate local Moran’s I, which focuses on cross-location correlation, we used local Lee’s L
54 to directly measure co-location correlation, for a more practical and interpretable spatially co-varying
55 association between ambient dust and SVI^{45,46}. For global and local Moran’s I and Lee’s L statistics
56 correlation, the queen adjacency neighbourhood definition was used so that contiguous polygons (here
57 SA1) sharing at least one border or vertex were considered spatial neighbours⁴¹⁻⁴⁴.
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v. Spatial generalised additive logistic regression

The ambient dust concentration was treated as a binary dependent variable using the $<$ median vs \geq median (low and high) and tertiles of the SVI score as the independent variable (low, moderate, and high). The low SVI category was used as the reference in the regression models. Ambient dust exposure and social vulnerability were categorised to facilitate comparison and accommodate potential non-linear relationships. Preliminary analyses using continuous variables and Generalised Additive Models (GAMs) with spline-based continuous forms showed that a linear specification did not adequately describe the association. For interpretability, the primary analyses used the categorised specifications, with spline-based continuous models included as a sensitivity analysis. The association between tertile SVI and binary ambient dust was estimated using GAMs logistic regression with thin-plate smoothing splines of the two-dimensional XY coordinates of SA1 as $s(Xcoord, Ycoord, bs = "tp")$ and applying the Robust Estimation of Maximum Likelihood method to prevent overfitting⁴⁷.

The model was fitted as

$Logit(Dust_{cat}) = SVI_{cat} + s(Xcoord, Ycoord, bs = "tp")$, where

i indicates a given SA1, $Dust_{cat}$ denotes the binary ambient dust exposure of SA1, SVI_{cat} is the tertile categories of SVI. Odds ratios (ORs) and 95% confidence intervals (CIs) were reported. An OR above 1 suggests greater odds of the outcome (high ambient dust) while ORs below 1 mean lower odds, and an OR of 1 shows no association between exposure and outcome. Precision is indicated by 95% CIs, with narrower CIs being more precise, and intervals excluding 1 suggest a likely association.

Subgroup analyses by remoteness (urban and rural), each SVI theme, and state were also performed. All three SVI themes were analysed simultaneously in one model for the main analysis, but separately in three separate models for sensitivity analyses. A standard (non-spatial) logistic regression was performed as a secondary analysis for all areas and separately for urban and rural areas to identify bias from ignoring spatial structure in the models.

3. Results

The 2021 annual average ambient dust concentration at the SA1 level across Australia ranged from 0.14 to 37.61 $\mu\text{g}/\text{m}^3$, with a mean (standard deviation) of 0.67 (0.90) $\mu\text{g}/\text{m}^3$ (Table S2, Figure 2), indicating moderate dust exposure within the global context (Figure S1).

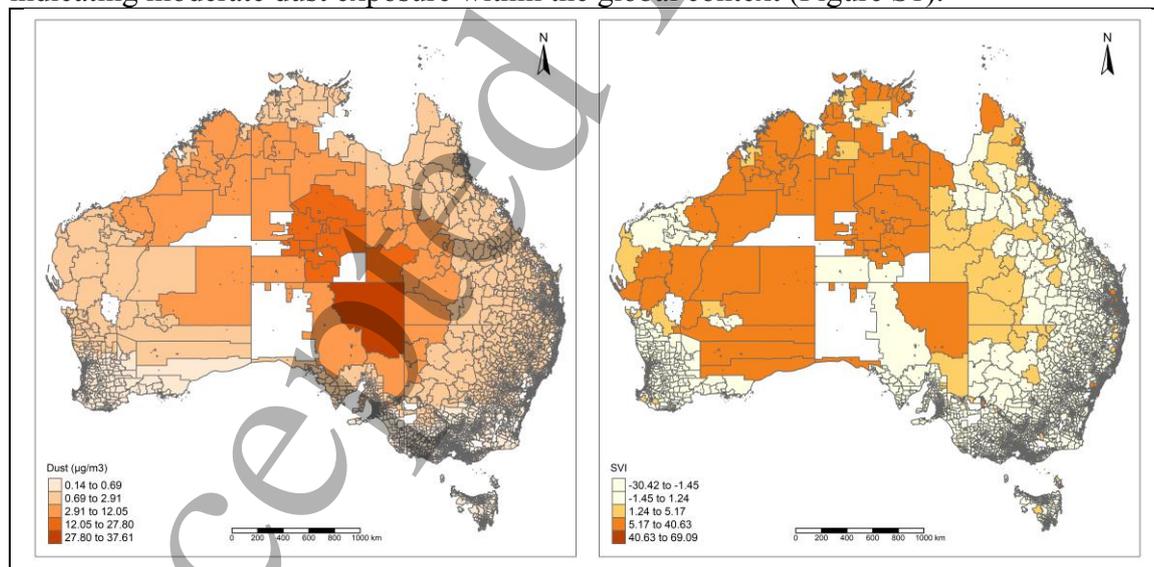


Figure 2. Spatial distribution of ambient dust exposure and social vulnerability index (SVI) across the included SA1 in Australia ($n = 55,177$). Note: Missing values were the SA1s excluded from the analysis due to populations of fewer than 50 people or missing dust concentrations.

The SVI ranged from -30.42 to 69.09 with a mean of -0.01 (2.96). From the choropleth maps, the overall SVI showed spatial variation similar to the ambient dust exposure (Figure 2). Univariate global

Moran's I indicated positive spatial autocorrelation, which was strong for ambient dust (Moran's $I=0.95$) and moderate for SVI (Moran's $I=0.48$). There was a small positive spatial correlation between SVI and ambient dust (Lee's $L=0.09$). Each SVI theme also showed positive spatial autocorrelation, ranging from global Moran's I of 0.31 (Themes 2: Demographic/Disability vulnerability and Theme 4: Housing vulnerability) to 0.78 (Theme 3: Cultural vulnerability).

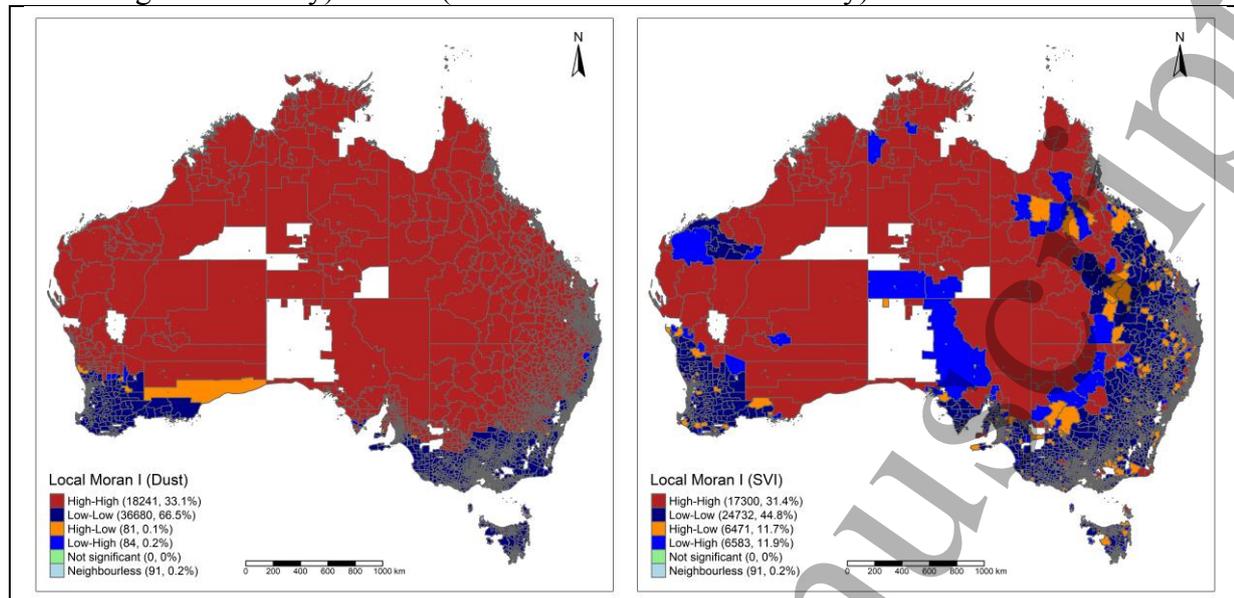


Figure 3. Univariate local Moran's index cluster map showing hotspots (High-High) and cold spots (Low-Low), and outlier areas (Low-High and High-Low) of ambient dust exposure and social vulnerability index (SVI) in Australia. Neighbourless refers to spatial units (statistical areal level 1) with no neighbours under the queen adjacency contiguity.

The spatial correlation between the SVI themes and ambient dust exposure from global Lee's L statistic ranged from -0.03 (Theme 1: Socioeconomic vulnerability and Theme 3: Cultural vulnerability) to 0.16 (Theme 5: Infrastructural vulnerability) (Table S3). Local Moran's I identified 18,241 (33%) SA1s as hotspots (High-High) and 36,680 (67%) SA1s as coldspots (Low-Low) for ambient dust, and 17,300 (31%) and 24,732 (45%) SA1s as hotspots and coldspots, respectively, for SVI (Figure 3).

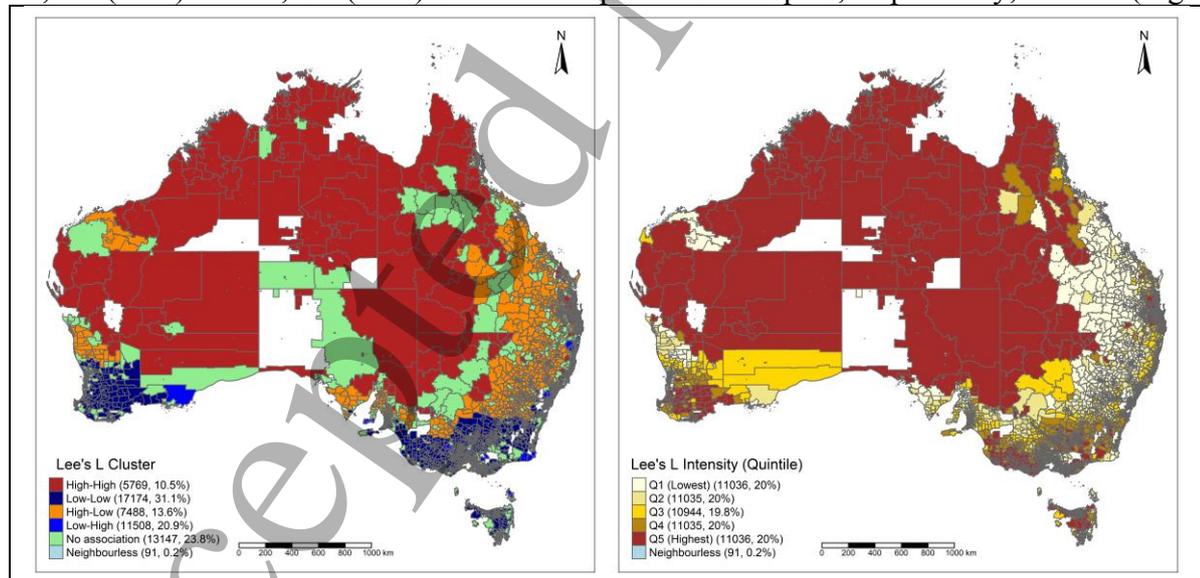


Figure 4. Bivariate local Lee's L cluster map (same-location correlation) showing areas with both high dust and SVI (High-High), both low dust and SVI (Low-Low), high dust and low SVI (High-Low), low dust and high SVI (Low-High), and no association between dust and SVI. The right map is the quintile classification of local Lee's L intensity. Neighbourless refers to spatial units (statistical areal level 1) with no neighbours under the queen adjacency contiguity. SVI, social vulnerability index.

Within each state/territory, the greatest percentage of hotspot areas was found in the Australian Capital Territory for ambient dust (60%) and in New South Wales for SVI (35%) (Figure S2). The bivariate local Lee's L choropleth map showed areas with spatial positive and negative correlations between ambient dust and SVI at the same location, with 5,769 (10.5%) SAIs showing co-location positive correlations of high ambient dust and high SVI across Australia (Figure 4) and variations within each state/territory (Figure S3). The ambient dust and SVI also exhibited cross-location correlations, as indicated by the bivariate local Moran's I (Figure S4).

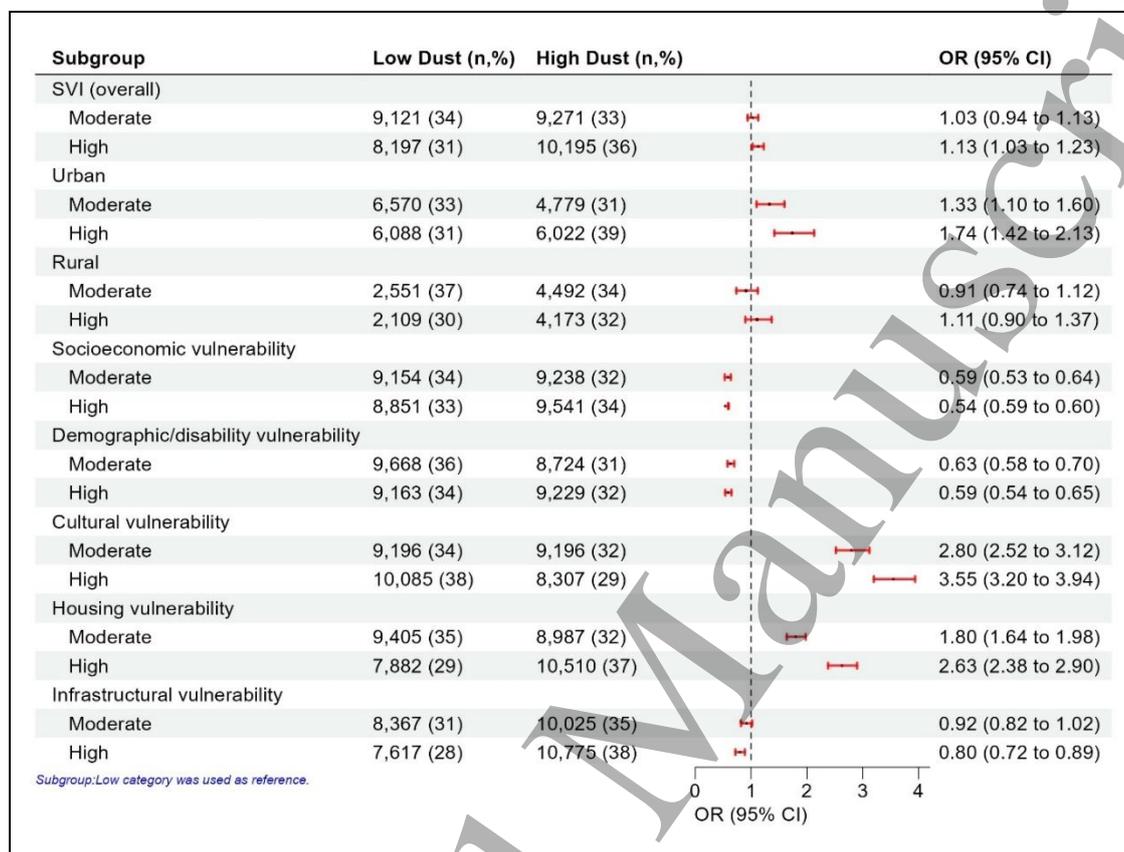


Figure 5. The odds of high ambient dust exposure with SVI overall and by remoteness (urban and rural), and for each SVI theme, using the low category as the reference. Note: SVI, social vulnerability index; OR, odds ratio; CI, confidence interval. The higher the vulnerability for both SVI overall and each subgroup, the greater the degree of vulnerability. Tertiles were used to define the Low, Moderate, and High categories of SVI and each subgroup. Binary dust exposure: Low (0) is $<$ median dust and High (1) is \geq median.

For high and low ambient dust exposure across the three categories of SVI, a relatively larger number of areas with high ambient exposure fell within the high SVI category (10,195 SA1; 36%). The distribution of ambient dust exposure levels by remoteness indicated that most urban areas had high ambient dust exposure, while most rural areas had moderate ambient dust exposure levels. There were also slight variations in ambient dust exposure levels within the categories of the SVI themes (Table 1). Relative to the low SVI, higher odds of high ambient dust exposure were found in both moderate and high SVI categories and were more elevated in the high SVI category (OR=1.13, 95% CI: 1.03, 1.23) than in the moderate SVI category (OR=1.03, 95% CI: 0.94, 1.13). The odds ratios of high ambient dust for the high relative to low SVI category were greater for urban areas (OR=1.74, 95% CI: 1.42, 2.13) than rural areas (OR=1.11, 95% CI: 0.90, 1.37). For the SVI themes, there were lower odds of high ambient dust in both moderate and high SVI categories compared to the low SVI category for Theme 1 (Socioeconomic vulnerability), Theme 2 (Demographic/Disability vulnerability), and Theme 5 (Infrastructural vulnerability). The lowest odds of high ambient dust exposure was 0.54 (95% CI: 0.49, 0.60) in the high SVI category for Theme 1 (Socioeconomic vulnerability). However, Theme 3 (Cultural vulnerability) and Theme 4 (Housing vulnerability) showed very strong odds of high

1
2 ambient dust exposure in both moderate and high SVI categories relative to the low SVI category. The
3 SVI theme with the strongest odds of high ambient dust exposure was Theme 3 (Cultural vulnerability),
4 which was more than three times stronger in the high SVI category relative to the low SVI category
5 (OR=3.55, 95% CI: 3.20, 3.94) (Figure 5, Table S4). For each state/territory, high ambient dust showed
6 greater odds in the high SVI category in Western Australia, Northern Territory, New South Wales
7 (both moderate and high SVI categories), Australian Capital Territory, and Tasmania. The most
8 elevated odds of high ambient dust was found in Tasmania (OR=5.03, 95% CI: 1.22, 20.7). In New
9 South Wales, the odds of high ambient dust were greater in the moderate (OR=1.29, 95% CI: 1.18,
10 1.42) than the high SVI category (OR=1.23, 95% CI: 1.12, 1.35) (Table S5).

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12
13 Results of the non-spatial model showed consistent directions of effect with the main analysis for SVI
14 overall and by remoteness. However, the effect estimates were biased with overestimation in non-
15 spatial models compared to the main analyses that integrated spatial components as smoothing splines
16 of the SA1 centroids (Table S6). Although the effect estimates showed only modest attenuation,
17 analyses of SVI themes in separate individual models were also consistent with the main analysis,
18 which included the five SVI themes together in a single model (Table S7). The spline-based continuous
19 forms with predicted dust at SVI percentiles and differences from the minimum predicted dust showed
20 a non-linear relationship (Table S8).

21 22 23 **4. Discussion**

24 25 *4.1 Main findings and interpretations*

26
27 In this study, we analysed the spatial association between ambient dust exposure and vulnerable
28 subpopulations in Australia using nationwide fine-grained SVI¹⁰ and a novel assessment of ambient
29 dust exposure²⁹. The results indicated geographical distributions and a positive association between
30 SVI and ambient dust exposure with hotspot locations. For specific SVI themes, negative associations
31 were found between ambient dust exposure and SVI for Theme 1 (Socioeconomic vulnerability),
32 Theme 2 (Demographics/Disability vulnerability) and Theme 5 (Infrastructural vulnerability), but
33 positive associations were found for Theme 3 (Cultural vulnerability) and Theme 4 (Housing
34 vulnerability). Cultural vulnerability, which was defined by minority groups and those with limited
35 English proficiency, experienced the strongest exposure to ambient dust. Our results also showed that
36 associations were stronger in the high than in the moderate SVI category, relative to the low SVI
37 category across all instances.

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41 Although there are no known studies specifically on ambient dust and social vulnerability or vulnerable
42 subpopulations, our results were consistent with the previous studies in Australia^{19,27,28}, other countries
43^{9,17,18,48-51} and globally^{11,21} showing positive associations between the spatial distribution of SVI or
44 selected vulnerable population indicators and ambient air pollution. The few Australian studies that
45 investigated the associations between SEIFA and other census-derived specific variables for SES with
46 NO₂ in urban areas²⁷, PM_{2.5} and NO₂ in both urban and rural areas¹⁹, and with sites and emissions
47 from industrial pollution sources²⁸ also found that lower-income, Indigenous, and ethnic minority
48 communities were disproportionately affected. The positive associations of high ambient dust
49 exposure with SVI in urban and rural areas suggest the pervasiveness of the disparities across the
50 country, as observed in previous findings for SEIFA indexes with PM_{2.5} and NO₂ in Australia¹⁹. That
51 previous study found consistent overall associations between rural and urban areas in Australia¹⁹, but
52 we found urban-rural disparity as the ambient dust-SVI association was stronger in urban than rural
53 areas, as reported in previous studies on air pollution and SVI in the United States^{52,53}, Korea⁵⁴ and a
54 2024 global study based on 2000-2019 data²¹. The higher ambient dust exposure and a stronger
55 positive association in urban areas than rural areas could be due to comparatively more vegetation in
56 rural areas than urban areas, characterised by higher populations, higher temperatures from the urban
57 heat island effect, and roads⁵⁴. Ambient dust from anthropogenic sources, such as building

1
2 construction and industrial activities in urban areas, tends to be higher than that from agricultural
3 activities predominant in rural areas.
4

5 For specific SVI themes, positive associations between ambient dust and Theme 3 (Cultural
6 vulnerability) and Theme 4 (Housing vulnerability) were consistent with similar previous findings that
7 Indigenous and ethnic minorities are more likely to be exposed to higher concentrations of ambient air
8 pollution^{19,27,28}. These subpopulations are also more likely to reside in rented and substandard houses
9 or areas with poor housing characteristics in peri-urban centres^{10,55}, prone to ambient dust infiltration,
10 making them more vulnerable to ambient dust exposure. Data on dust infiltration, outdoor occupations,
11 and place-time activity patterns would be needed for a more accurate assessment of vulnerability.
12 Moreover, the negative association between ambient dust and Theme 5 (Infrastructure vulnerability)
13 suggests that a highly built environment offers protection from ambient dust exposure. Surprisingly,
14 the negative associations between ambient dust exposure and SVI for Theme 1 (Socioeconomic
15 vulnerability) and Theme 2 (Demographics/Disability vulnerability) indicated areas with high levels
16 of poor SES and high percentages of older adults and children and those not in labour force and needing
17 childcare, and disabled individuals experienced low ambient dust exposure. While these unexpected
18 results deserve further investigation, it could be that these vulnerable subpopulations were more
19 prevalent in rural or peri-urban areas where ambient dust exposure was low.
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23 Given the observed spatial autocorrelations for both ambient dust and SVI, the consistent but
24 overestimated effect estimates from the non-spatial models are explainable by biases from not
25 accounting for the spatial autocorrelation or spatial effect, leading to more false-positive findings in
26 the non-spatial models^{54,56}. Thus, accounting for spatial autocorrelation or location is important and
27 should be considered in environmental justice studies^{54,56}.
28
29

30 Our findings support the proposition of environmental injustice, where certain groups and locations of
31 the subpopulations are at a higher risk of ambient dust exposure^{3,12-15,57,58}. Urban areas and
32 communities experiencing cultural, ethnic/racial minority, or housing vulnerability were
33 disproportionately exposed to ambient dust. These inequities reflect policy decisions and broader
34 social structural processes, such as residential segregation, discriminatory lending, and inequitable
35 land use, that place marginalised groups closer to major anthropogenic sources of dust and other co-
36 occurring environmental hazards, such as toxic chemicals, air pollution, and extreme climate change-
37 related events (e.g., heatwaves, bushfires, natural disasters)^{3,12-15}. Although ambient dust is mainly
38 natural, human activities such as land clearing, construction, industrial and transport infrastructure,
39 and reduced vegetation can intensify emissions, and urbanisation may further concentrate exposure.
40 Similar to previous studies on ambient air pollution and SVI indicators^{9,17-19,27,28,48-54}, we did not assess
41 whether these associations translate to adverse health outcomes. Nonetheless, the findings are very
42 relevant to public health interventions and policymaking for the reason that ambient dust is
43 predominantly particulate matter (PM_{10-2.5} and PM₁₀) by mass, and recent systematic reviews and
44 meta-analyses found that high concentrations of PM_{10-2.5} and PM₁₀ during dust storm events were
45 associated with several health effects and mortality⁵⁻⁷. Recent scoping reviews have also documented
46 that SVI indicators relate to the health impacts of climate change and predict disaster response, and
47 health outcomes^{59,60}.
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51 The vulnerable subpopulations are more susceptible to negative health outcomes directly or from
52 environmental exposures, including ambient dust exposure through social stratification and underlying
53 determinants of health inequalities, consistent with environmental justice frameworks^{5,16,19,57,61}.
54 Therefore, any policy decisions and interventions targeted to make even small differences in reducing
55 environmental injustice could benefit the entire population, with potentially larger benefits for high-
56 risk subpopulations^{57,62}. Although ambient dust cannot be completely controlled, targeted mitigation
57 and adaptation strategies are required, which could include sustainable land management (e.g., soil
58 conservation, reforestation, and sustainable agriculture to reduce desertification) and climate
59
60

1
2 resilience. Infrastructural and public health policies are also required to withstand extreme weather
3 events, reduce dust generation or emissions (e.g., road maintenance, dust suppression at industrial and
4 construction sites), and protect air quality. Health monitoring, early dust warning systems, and
5 provision of healthcare support during extreme dust storm events, especially for vulnerable
6 subpopulations, are also critical. Areas identified as hotspots with high vulnerability and high ambient
7 dust exposure could be targeted for interventions.
8

9
10 Our key findings provide far-reaching policy implications for vulnerable subpopulations by taking into
11 account health, environment, geographical location, and social vulnerability dimensions. Future
12 corresponding public health and environmental health studies to demonstrate and quantify
13 disproportionate health effects of ambient environmental exposures, including ambient dust exposure
14 in vulnerable subpopulations, are recommended^{19,57}. Moreover, individual-level assessment of the
15 ambient dust exposure will be more helpful. Recent scoping reviews have indicated that, despite the
16 contextuality of SVI, using limited social vulnerability indicators, mostly restricted to
17 sociodemographic and socioeconomic variables, may not adequately capture the SVI metric for public
18 health and environmental justice assessments required for appropriate interventions and policy
19 making, including climate adaptation planning^{59,60}. Therefore, detailed information on housing
20 characteristics and additional inclusion of different data sources on the built environment as used by
21 the US Centres of Disease Control and Prevention to construct SVI³⁴, especially the '4D'
22 quantification of the built environment (diversity, design, density, and distance) by Wang *et al*¹⁰
23 to construct the SVI used in our study could be considered in future studies.
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26
27 By linking social vulnerability to ambient dust exposure, this study highlights how environmental
28 hazards intersect with structural inequities, underscoring the need for equity-focused interventions.
29 This study also provides a generalisable framework for identifying ambient dust-vulnerability
30 associations and hotspots that can be updated as data and modelling tools advance to inform future
31 environmental justice assessments and related climate adaptation planning strategies.
32

33 *4.2 Strengths and Limitations*

34 To the best of our knowledge, this is the first study to specifically examine ambient dust and SVI in
35 Australia and among the first globally. The SVI metric additionally included detailed information on
36 housing, transport, and the built environment, together with four-dimensional quantification of the
37 built environment¹⁰, providing another strength of this study. The ambient dust concentration was
38 obtained from a new assessment of global and regional budgets, fluxes, and lifetimes of atmospheric
39 reactive species and aerosols²⁹. The analytical frameworks were robust, including global and local
40 univariate and bivariate spatial autocorrelations and correlations, and spatial smoothing generalised
41 additive models at the fine-grained spatial units as SA1.
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45 Similar to the previous studies^{9,17-19,27,28,48-54}, this is a cross-sectional study to investigate correlation,
46 but not causation, which is usual with this topic because of the inability to randomise dust exposure in
47 observational research. The annual average ambient dust concentration may contribute to
48 understanding overall long-term exposure, but it is not well-suited for capturing acute dust events such
49 as episodic dust storms and peaks from anthropogenic activities and seasonal variability in dust
50 emissions. Although one of the smallest geographical units in Australia (SA1) was reported in this
51 study, ecological fallacy cannot be ruled out, as the findings from SA1-level analysis may be different
52 from individual-level analysis. More temporally and spatially refined data on ambient dust exposure
53 and SVI at the individual level would allow more precise quantification of environmental justice in
54 ambient dust exposure and SVI. Finally, this study did not examine the composition of the ambient
55 dust.
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5. Conclusion

This national study identified spatial variability with several identified hotspot areas and positive associations between SVI and ambient dust exposure, particularly elevated in the urban areas. For SVI themes, strong positive associations were found in Cultural and Housing vulnerabilities. Interestingly, we observed negative associations for Socioeconomic, Demographic/Disability, and Infrastructural vulnerabilities. Targeted ambient dust or air pollution reductions are essential to provide all people and areas with a level of protection from environmental exposures to mitigate the environmental injustice of ambient dust and other co-occurring environmental hazards. Further studies should examine the composition and duration of the ambient dust and SVI and the corresponding health outcomes to guide preventative public health measures and policy decisions.

Data and code availability

The processed area-level dataset generated during this study is publicly available at Zenodo (<https://doi.org/10.5281/zenodo.18811539>).

The source Social Vulnerability Index (SVI) data and further information are available at the Harvard China Data Lab project page (https://projects.iq.harvard.edu/chinadatalab/AU_vulnerability) and from Wang et al. (2022)¹⁰.

The chemical transport model code used to generate the 2021 EMEP-WRF ambient mineral dust used in this study is publicly available at <https://github.com/metno/emep-ctm>.

Geographic boundaries were based on the 2016 Australian Statistical Geography Standard (ASGS) shapefiles provided by the Australian Bureau of Statistics (Catalogue No. 1270.0.55.001, July 2016 release), which are publicly accessible from the ABS website (<https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July%202016>).

No individual-level data were used or generated in this study.

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Author contributions

SDN and GP designed the study. SDN performed data curation and formal data analyses and wrote the initial draft of the manuscript. GP contributed to the data analyses. MV developed and quantified the ambient dust exposure. SW developed and quantified the social vulnerability index. GAT critically reviewed the manuscript. All authors contributed to critical review and editing and approved the final manuscript.

Ethical approval

Not applicable

Conflict of interest

The authors declare no competing interests.

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Table 1. Distribution of ambient dust exposure levels by social characteristics in Australia
(N= 55,177 SAIs)

Variable#	Low ambient dust exposure* (N = 26,747 SAIs), n (%)	High ambient dust exposure* (N = 28,430 SAIs), n (%)
SVI (Overall)		
Low	9,429 (35)	8,964 (32)
Moderate	9,121 (34)	9,271 (33)
High	8,197 (31)	10,195 (36)
<i>Remoteness</i>		
Urban		
Low	7,140 (36)	4,535 (30)
Moderate	6570 (33)	4779 (31)
High	6088 (31)	6022 (39)
Rural		
Low	2,289 (33)	4429 (34)
Moderate	2551 (37)	4492 (34)
High	2109 (30)	4173 (32)
<i>Themes</i>		
Theme 1 (Socioeconomic vulnerability)		
Low	8,742 (33)	9,651 (34)
Moderate	9,154 (34)	9,238 (32)
High	8,851 (33)	9,541 (34)
Theme 2 (Demographic/disability vulnerability)		
Low	7,916 (30)	10,477 (37)
Moderate	9,668 (36)	8,724 (31)
High	9,163 (34)	9,229 (32)
Theme 3 (Cultural vulnerability)		
Low	7,466 (28)	10,927 (38)
Moderate	9,196 (34)	9,196 (32)
High	10,085 (38)	8,307 (29)
Theme 4 (Housing vulnerability)		
Low	9,460 (35)	8,933 (31)
Moderate	9,405 (35)	8,987 (32)
High	7,882 (29)	10,510 (37)
Theme 5 (Infrastructural vulnerability)		
Low	10,763 (40)	7,630 (27)
Moderate	8,367 (31)	10,025 (35)
High	7,617 (28)	10,775 (38)

Note: SVI, Social Vulnerability Index

#For both SVI overall and thematic vulnerabilities, the higher the vulnerability score the greater the degree of vulnerability. Low, Moderate, and High categories of SVI and individual themes were defined using tertiles.

*Binary dust: Low is < median dust and High is ≥ median dust exposure.