Associations between historical residential redlining and current age-adjusted rates of emergency department visits due to asthma across eight cities in California: an ecological study

Anthony Nardone, Joan A Casey, Rachel Morello-Frosch, Mahasin Mujahid, John R Balmes, Neeta Thakur

Summary

Background Asthma disproportionately affects communities of colour in the USA, but the underlying factors for this remain poorly understood. In this study, we assess the role of historical redlining as outlined in security maps created by the Home Owners' Loan Corporation (HOLC), the discriminatory practice of categorising neighbourhoods on the basis of perceived mortgage investment risk, on the burden of asthma in these neighbourhoods.

Methods We did an ecological study of HOLC risk grades and asthma exacerbations in California using the security maps available for the following eight cities: Fresno, Los Angeles, Oakland, Sacramento, San Diego, San Jose, San Francisco, and Stockton. Each census tract was categorised into one of four risk levels (A, B, C, or D) on the basis of the location of population-weighted centroids on security maps, with the worst risk level (D) indicating historical redlining. We obtained census tract-level rates of emergency department visits due to asthma from CalEnviroScreen 3.0. We assessed the relationship between risk grade and log-transformed asthma visit rates between 2011 and 2013 using ordinary least squares regression. We included potential confounding variables from the 2010 Census and CalEnviroScreen 3.0: diesel exhaust particle emissions, $PM_{2.5}$, and percent of the population living below 2 times the federal poverty level. We also built random intercept and slope models to assess city-level variation in the relationship between redlining and asthma.

Findings In the 1431 census tracts assessed (64 [4·5%] grade A, 241 [16·8%] grade B, 719 [50·2%] grade C, and 407 [28·4%] grade D), the proportion of the population that was non-Hispanic black and Hispanic, the percentage of the population living in poverty, and diesel exhaust particle emissions all significantly increased as security map risk grade worsened (p<0·0001). The median age-adjusted rates of emergency department visits due to asthma were 2·4 times higher in census tracts that were previously redlined (median 63·5 [IQR 34·3] visits per 10 000 residents per year [2011–13]) than in tracts at the lowest risk level (26·5 [18·4]). In adjusted models, redlined census tracts were associated with a relative risk of 1·39 (95% CI 1·21–1·57) in rates of emergency department visits due to asthma compared with that of lowest-risk census tracts.

Interpretation Historically redlined census tracts have significantly higher rates of emergency department visits due to asthma, suggesting that this discriminatory practice might be contributing to racial and ethnic asthma health disparities.

Introduction

Asthma is the most racially and ethnically disparate health condition in the USA.[1] Compared with non-Hispanic white populations, asthma is 1·25 times as common and nearly 3 times as likely to cause death in non-Hispanic black individuals.[2] Decades of scientific research have documented this disparity and have attempted to explain it by estimating the contribution of exposures concentrated in communities of colour, including ambient air pollution, poverty, psychosocial stress, and insufficient health care and medication access.[3–7] To our knowledge, few studies have considered historical policies that might explain the concentration of these social and environmental factors in communities of colour.[8–11] We sought to assess whether historical discriminatory policies that shaped neighbourhood development in the USA are associated with asthma-related health disparities.

In 1933, the Home Owners' Loan Corporation (HOLC) was formed under the New Deal initiative as a depression-era measure to refinance defaulted home mortgages and prevent foreclosures. To efficiently assess applicants' risk, HOLC generated security maps that categorised urban neighbourhoods into one of four perceived

Research in context

Evidence before this study

We searched PubMed, Web of Science, and Embase for studies assessing the relationship between historical residential redlining maps and present-day health outcomes published before May 31, 2019, with the terms "redlining" AND "health redlining" AND "asthma". We identified three articles focused on historical redlining and subsequent societal wellbeing: an observational study of redlining maps and subsequent tuberculosis cases in Austin, Texas, in the 1950s; an analysis of historical redlining and modern crime rates in Philadelphia, Pennsylvania; and a study of how historical redlining was associated with self-rated mental health and foreclosure rates during the subprime mortgage crisis in Detroit, Michigan.

Added value of this study

To our knowledge, this is the first study to assess the relationship between asthma health outcomes and historical redlining. Additionally, this is also the first study to assess the

potential health impacts of redlining in eight metropolitan areas across California. Our analysis included 2011–13 data from 1431 census tracts. We found that median age-adjusted rates for emergency department visits due to asthma were 2·4 times higher in historically redlined census tracts than in tracts that were not redlined in the 1930s. Asthma emergency visit rates in redlined census tracts remained significantly elevated after adjusting for present-day poverty rate, diesel particle emissions, $PM_{2.5}$, and spatial autocorrelation.

Implications of all the available evidence

Historical redlining, enforced over 80 years ago in more than 200 cities across the USA, might contribute to present-day asthma health outcomes in the urban census tracts of California. Similar research in other geographical regions and with individualised data should be done to assess the generalisability of these findings.

foreclosure risk groups.[12] Neighbourhoods that were predominantly inner-city, black, and immigrant were systematically graded as hazardous and outlined in red, whereas neighbourhoods with higher property value, better housing quality, and less "infiltration" by people of colour and "foreign-born" individuals (terms used in HOLC appraisal forms) were considered lower risk.[12] This practice of residential redlining that was derived, systematised, and disseminated by the federal government and adopted by the private sector has had extended effects by entrenching racial segregation and diminishing the appreciation of home values and accumulation of wealth.[12–14] In tandem with redlining, other policies in effect at multiple legislative levels, such as eminent domain and racial zoning, also affected where schools, highways, and toxic-hazard sites were placed, leaving behind a patchwork legacy of security maps and segregation in cities across the USA.[8] Across the country today, previously redlined neighbourhoods are of predominantly low-to-moderate income, with higher levels of income inequality than other neighbourhoods, and comprised mainly of communities of colour, with greater levels of segregation than neighbourhoods that were not redlined.[11] These segregated communities of colour have higher poverty, higher unemployment, higher violent crime rates, higher levels of industrial pollution, lower home ownership, and are more likely to be identified as medically underserved than non-segregated communities.[15,16] As such, asthma exacerbations are of particular interest regarding redlining, because neighbourhood-level asthma-related exposures, such as air pollution, psychosocial stress, and insufficient access to care, might be concentrated in these neighbourhoods partly because of these policies.[8,9]

HOLC maps also propelled divestment from perceived high-risk communities, influenced so-called white flight

and urban decline, and probably contributed to subsequent disparities in housing quality and the ever-growing racial wealth gap.[8,14,17] Furthermore, intergenerational relationships exist between socioeconomic status and psychosocial stress and asthma, and these might bolster the possibility that trauma imparted by racially discriminatory policies, such as redlining, can influence the health of future generations.[18] At minimum, these maps reflected, with geographical specificity, the norms and values held by gatekeepers of financing, wealth, and equity-generating resources, allowing for unique spatial analyses that can assess how historic policies contributed to present-day health disparities. To advance our understanding of the potential origins and persistence of racial and ethnic disparities in asthma burden, we examined the association between residential redlining, the government sponsored practice of racially discriminatory mortgage appraisal and lending strategies during the 1930s and 40s, and present-day asthma-related emergency department visits in California.

Methods

Study design and security maps

For this study, we adopted an ecological study design at the census tract level. We included security maps created by HOLC from 1935 onwards for eight cities in California (USA): Fresno, Los Angeles, Oakland, Sacramento, San Diego, San Francisco, San Jose, and Stockton. Security maps from Oakland and Los Angeles contained multiple municipalities and are referred to as metropolitan areas for the purpose of this analysis (appendix pp 2–3). Security maps are publicly available and were downloaded from the University of Richmond's Mapping Inequality Project.[19] Neighbourhoods appraised by HOLC were shaded in one of four colours denoting risk, from lowest to highest: green (best), blue (still desirable), yellow (declining), and red

See **Online** for appendix

(hazardous).[19] Neighbourhoods considered redlined were those shaded in red, receiving a hazardous designation. We refer to these HOLC-defined risk levels as HOLC risk grades. Each map colour was assigned a letter grade of A, B, C, and D, with A being the lowest perceived risk grade (ie, green or best) and D or redlined being the highest perceived risk (ie, red or hazardous). The main predictor of interest was HOLC risk grade of each census tract. Every 2010 census tract was assigned a HOLC risk grade by superimposing 2010 census tract centroids onto HOLC security maps (appendix p 1).

Outcome and covariate data

Asthma emergency department visit rates, air pollution, and demographic data were acquired from CalEnviroScreen 3.0 (CES3.0).[20] CES3.0 is a dataset created by the California Office of Environmental Health Hazard Assessment that merges health outcome data with outdoor environmental pollution data and demographic statistics from across the state at the census tract level. For this study, we used a census-tract proxy of asthma-related health burden by assessing total age-adjusted rates of emergency department visits due to asthma per 10 000 residents per year between 2011 and 2013. These rates reflect the total number of emergency department visits accumulated by residents of all ages from that census tract over the 3-year period; rate calculations have been explained elsewhere.[21] Inclusion of covariates in our models was determined a priori by associations identified in existing asthma literature and inclusion in CES3.0.[3,22] Specifically, we included the following census tract-level variables: percentage of population living below 2-times the federal poverty threshold in 2010, the 3-year average $PM_{2.5}$ in $\mu g/m^3$ from 2012–14, and the estimated diesel exhaust particle (DEP) emissions (kg) for a summer day in 2012.[21]

Statistical analysis

In descriptive analyses, we assessed the distribution of study variables and bivariate associations between HOLC risk grades, average rates for asthma emergency department visits, demographic data from the 2010 census, and other study covariates using ANOVA. Visit rates were compared across HOLC risk grades by use of ANOVA, and subsequent comparisons of visit rates by HOLC grade were done with the Tukey-Kramer test. Census tract choropleth maps were generated with the GISTools R package to assess the qualitative associations between security maps and present asthma emergency room visit rates at the census tract level.[23]

We built preliminary ordinary least squares regression models to assess the relationship between natural log-transformed visit rates and redlining when adjusted for potential confounders. We selected ordinary least squares regression with a natural log-transformed outcome over Poisson regression to handle age-adjusted rates. We present our findings as back-transformed

regression coefficients, calculated by exponentiation of model coefficients, and used the delta method to calculate coefficient SEs.[24] Back-transformed coefficients can be interpreted as the times increase in the age-adjusted visit rate.

Residual spatial dependence might arise from the spatially dependent nature of emergency department visit rates and the clustering of environmental factors in neighbouring census tracts. We built random intercept and slope models using the lme4 R package to address this potential model assumption violation.[25] Random intercepts were included at the city level, with each intercept corresponding to a different security map. Random slopes allowed us to estimate differential relationships by city between the HOLC risk grade and visit rate. Random slope models were included because, during the time of residential redlining in the 1930s and 40s, various policies were enforced across multiple legislative levels, from the federal level (redlining) down to state and local government levels, and because HOLC risk grade assignment varied by city (appendix p 1).[8]

In a sensitivity analysis, we identified the presence of spatial autocorrelation using Moran's I.[26] Therefore, we built a conditional autoregression model using the spdep package in R, because ordinary least squares models might produce biased results in the presence of residual spatial autocorrelation (appendix p 2).[27] Compared with mixed-effects models, which compare census tracts within a given city, the conditional autoregression accounts for potential relationships between neighbouring census tracts.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. All authors had full access to all the data in the study and made the decision to submit for publication.

Results

Of the 3696 census tracts from eight Californian cities in our sample, we excluded 2265 (61·3%) because tract

	Grade A (n=64)	Grade B (n=241)	Grade C (n=719)	Grade D (n=407)	p_{trend}
Percentage Hispanic	10·9% (8·8)	27·6% (27·3)	46·5% (28·1)	55·5% (30)	<0·0001
Percentage non-Hispanic Asian	12·2% (12·2)	15·8% (17·4)	14·9% (17·0)	12·9% (14·9)	0·070
Percentage non-Hispanic Black	6·2% (16·1)	8·5% (16·2)	10·1% (12·5)	10·9% (13·7)	0·021
Percentage non-Hispanic White	67·1% (22·6)	44·8% (28·4)	25·9% (26·6)	18·3% (21·9)	<0·0001
Percentage other	3·5% (1·0)	3·1% (1·5)	2·4% (1·5)	2·2% (1·6)	<0·0001
Percentage of poverty*	15·6% (9·4)	29·7% (17·2)	47·3% (19·9)	51·9% (19·9)	<0·0001
Mean $PM_{2.5}$ ($\mu g/m^3$)	11·1 (1·6)	11·0 (1·6)	11·5 (1·4)	11·4 (1·6)	0·0003
Mean diesel PM (kg/day)	22·6 (14·3)	27·8 (16·2)	29·8 (15·9)	39·7 (23·5)	<0·0001

Data are mean (SD); n indicates the number of census tracts. HOLC=Home Owners' Loan Corporation. PM=particulate matter. *Defined by the percentage of the population living below two-times the federal poverty level.

Table 1: Socio-demographic and air pollution characteristics of census tracts by previous HOLC risk grade
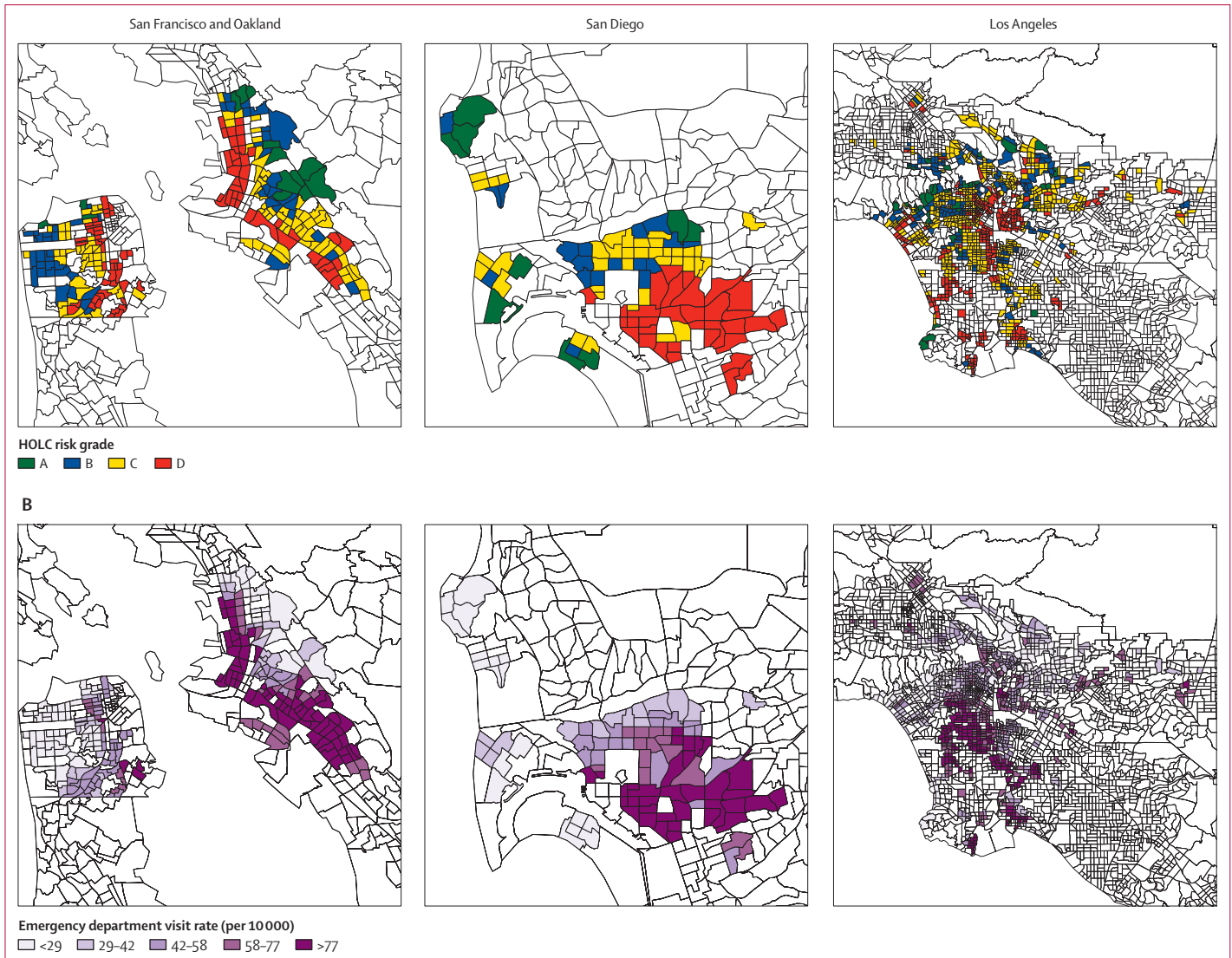
Figure 1: 2010 census tracts categorised by HOLC risk grade (A) and total age-adjusted rates of emergency department visits for asthma in 2011–13 (B) across three metropolitan areas in California

Census tracts shaded white were not categorised and were excluded from the analysis. HOLC=Home Owners' Loan Corporation.

centroids were in uncategorised regions (areas that HOLC appraisers included on maps, but did not assign risk grades) leaving 1431 (38·7%) tracts in the final analytical sample. Of the 1431 census tracts assigned a HOLC risk grade, the largest proportion received grade C (719 tracts [50·2%]), followed by D (407 [28·4%]), B (241 [16·8%]), and A (64 [4·5%]; table 1). We observed significant trends across demographic groups, poverty rate, and air pollutant exposures. The percentage of non-Hispanic black and Hispanic populations both increased as risk grade worsened. By contrast, we observed the opposite trend in the percentage of non-Hispanic white individuals within a census tract: A-rated tracts contained 67·1% non-Hispanic white individuals compared with 18·3% in D-rated tracts. Poverty rate was 3·3 times

higher in D-rated (redlined) tracts than in A-rated tracts, with over half of residents living on average 2-times below the federal poverty level in D-rated tracts. Estimated DEP emissions in D-rated tracts were nearly twice that of those in A-rated tracts. Uncategorised tracts had demographics, poverty rate, and air pollutant measures closer to those of Grade B and C tracts than of other tracts (appendix p 1).

In the San Francisco and Oakland metropolitan areas (246 census tracts), San Diego (98 tracts), and Los Angeles metropolitan area (1015 tracts), HOLC risk grades appear to spatially correlate with age-adjusted rates of emergency department visits due to asthma (figure 1). Median asthma-related visit rates in D-rated tracts (63·5 [IQR 29·2–97·8] visits per 10 000 residents per year

[2011–13]) were 2·4 times higher than in A-rated tracts (26·5 [8·0–44·9]) and 1·7 times higher than in B-rated tracts (37·9 [6·7–69·1]; figure 2). C-rated tracts had median visit rates between those of B-rated and D-rated tracts (52·6 [IQR 14·5–90·8] visits per 10 000 residents). In an unadjusted linear regression model, HOLC risk grade was a significant predictor of rates of emergency department visits due to asthma (p<0·0001).

Adjusted ordinary least squares regression showed a significant relationship between worsening HOLC grade and asthma visit rates at the census tract level (table 2). Predicted values from the adjusted ordinary least squares model, holding other variables at their mean, showed that historical redlining (grade D) was associated with an age-adjusted 15·6 (95% CI 8·8–23·3) additional emergency department visits due to asthma per 10 000 residents per year. The random intercept (city-level) mixed model was consistent with the main findings (table 2). When we added a random slope, the Oakland metropolitan area, San Diego, and San Francisco had the strongest relationships between HOLC risk grade and rates of emergency department visits due to asthma (appendix p 1). The sensitivity analysis, using a conditional autoregression model that accounted for spatial autocorrelation, was consistent with the main results (appendix p 2).

Discussion

To achieve racial and ethnic health equity, it is crucial to understand how historically discriminatory policies might influence health disparities today. Our results indicate that redlining policies that denied wealth-generating opportunities in communities of colour and undermined the physical environments of neighbourhoods might have affected present-day asthma-related outcomes across eight cities of California.[8,14]

To our knowledge, this is the first study to examine the association between historical government-sponsored redlining practices and age-adjusted rates of emergency department visits due to asthma. Two other studies have been published that examined historical redlining as a driver of present-day health. McClure and colleagues[10] observed that historical redlining, as defined by security maps, functioned as a confounder of the association between mortgage disclosure rates and self-rated health during the subprime mortgage crisis between 2008 and 2013 in Detroit, Michigan (USA). In a study in Austin, Texas, Huggins[28] found that rates of tuberculosis cases were a maximum of 20-times higher in redlined neighbourhoods than in non-redlined neighbourhoods in 1952. Both these previous studies considered only redlined neighbourhoods (grade D) as exposed, whereas our analysis extended these findings by assessing and identifying poorer health outcomes not only in redlined neighbourhoods, but also in B-rated and C-rated neighbourhoods, compared with those of A-rated areas.
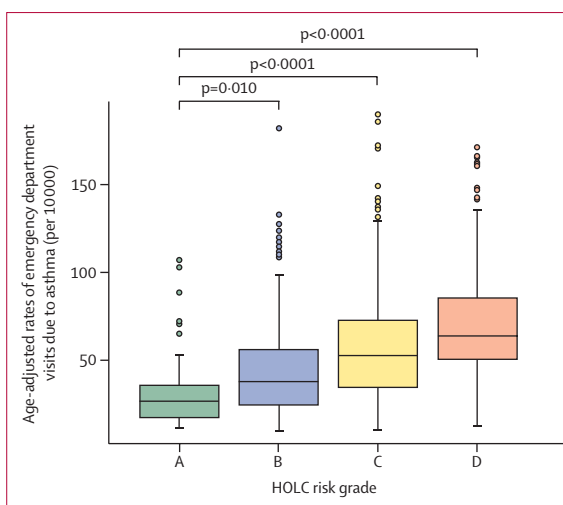

Figure 2: **Age-adjusted rates of emergency department visits due to asthma by HOLC risk grade**
Reported p values were calculated with the Tukey-Kramer test. HOLC=Home Owners' Loan Corporation.

	Grade B	Grade C	Grade D
Unadjusted OLS	1·42 (1·22–1·62)	1·85 (1·60–2·10)	2·34 (2·02–2·66)
Adjusted OLS*	1·14 (1·00–1·28)	1·18 (1·03–1·33)	1·39 (1·21–1·57)
MEM-random intercept†	1·24 (1·09–1·39)	1·30 (1·15–1·45)	1·53 (1·34–1·72)
MEM-random slope‡	1·15 (0·99–1·31)	1·29 (1·09–1·49)	1·54 (1·08–2·00)

Data are relative risk (95% CI). Asthma ED-visit rates were natural log-transformed, and estimates were back-transformed by exponentiation and can be interpreted as the times increase in rates of emergency department visits due to asthma compared with grade A census tracts. 95% CIs were calculated with the delta method. HOLC=Home Owners' Loan Corporation. MEM=mixed-effects model. OLS=ordinary least squares. *Adjusted for poverty rate, diesel exhaust particle emissions, and $PM_{2.5}$ level. †Random intercepts were generated at the city level and corresponded to each of the maps included in the analysis. ‡Random slopes were generated for HOLC grade at the city level.

Table 2: **Association between HOLC risk grade and age-adjusted asthma ED-visit rates across 1431 California census tracts, 2011–13**

Other studies have assessed how modern forms of redlining are associated with health outcomes. In these studies, neighbourhoods redlined by these modern forms currently have higher rates of mortgage and insurance coverage denial, yet also have improved mental and physical health.[29,30] These findings with modern redlining are contrary to the associations we identified with historical redlining. The evidence of economic and health benefits of living in so-called ethnic enclaves is mixed. Some studies suggest that some immigrant communities of colour overcame discriminatory policies denying them financing by creating their own financial networks that enable access to credit for investing in their property.[29,31] Additionally, the context in which black and Hispanic populations were subjected to different forms of historical racism and thereby segregated probably has produced current dynamics unique from immigrant enclaves that were formed through other racist policies. However, to our knowledge, no studies have considered the relationship

between modern forms of redlining and historical redlining.

Regarding the social and physical aspects of neighbourhoods, we found that historically redlined census tracts had DEP emission estimates nearly twice as high as in A-rated tracts. Highways, a major source of diesel emissions, were often constructed in the 1940s and 50s in so-called blighted areas, where community resistance to land acquisition was weakest and probably overlapped with areas categorised as hazardous by HOLC security maps.[8] This history of freeway construction might partly explain the higher ambient air pollutant concentrations associated with asthma at the homes and schools of communities of colour compared with those in predominantly white neighbourhoods.[3,32] Additionally, we found that poverty rates were 3·3 times higher in historically redlined census tracts than in grade A tracts, a relationship similar to that identified by Mitchell and colleagues across 115 cities in the USA.[11] Neighbourhood-level and individual-level low socioeconomic status and high psychosocial stressors, including neighbourhood violence, have been shown to contribute to asthma incidence, prevalence, and severity.[33,34]

Another mechanism by which historical redlining might affect asthma is through racially disparate forms of wealth acquisition. Americans living in redlined neighbourhoods who were denied financing missed out on home ownership opportunities or lost home value appreciation.[14] This disparity in opportunities to build home equity is reflected by the persistent racial and ethnic wealth gap in the USA, in which an African-American family owns an average of US$11 000 in assets, whereas a white family owns 13 times that amount—an average of $142 000.[17] The inability to accumulate wealth can ultimately affect asthma risk by reducing quality housing options and ability to buffer stress.[35]

Similar to Mitchell and colleagues' findings, we identified that historically redlined census tracts have higher percentages of non-Hispanic black and Hispanic populations than those of higher-graded tracts.[11] The practice of historical redlining contributed to and solidified segregation. Michney and colleagues found that, although HOLC lending patterns did not align with the risk delineated by their security maps, the lending policy reinforced pre-existing segregation at the time of the maps' use.[13] Such forms of structural discrimination that shaped spatial patterns of disinvestment can undermine the socioeconomic and physical environments of neighbourhoods in ways that can amplify health disparities.[36] Although existing forms of discrimination in housing might affect health disparities, the resulting racial segregation in the USA is associated with various health risks and adverse health outcomes.[37,38] Given that racial and ethnic disparities in asthma outcomes seem to disproportionately burden Hispanic and black populations, who are also more likely to live in census tracts with higher DEP emissions and poverty rates, our findings suggest that historical redlining might have a role in the confluence of these factors in California.

Redlining, through the creation of security maps, encouraged discriminatory categorisation of neighbourhoods on the basis of racial demographics, thus eroding the reputations of low-graded neighbourhoods and subsequent investment or divestment.[14] For example, the presence of green spaces might reflect previous infrastructure investment, which is influenced by land ownership and government involvement. Previous studies have identified that people of colour and those with low incomes are more likely to live in neighbourhoods that lose more green spaces over time than white individuals.[39] Although green spaces are associated with various health outcomes, the presence of trees is associated with significantly less ambient nitrogen dioxide, a traffic-related air pollutant strongly implicated in racial asthma disparities.[40] Additionally, the practice of redlining might influence the placement of health-care services, thus potentially limiting future access to care and hence, might contribute to existing asthma disparities.[16,41]

Furthermore, the historical context upon which institutions in these communities function can perpetuate inequity. For example, two studies published in the past few years found that historical concentrations of enslaved populations during the 1800s in the southern USA are associated with present-day poor health outcomes.[42,43] Although a historically racist practice has been abolished, the underlying discriminatory mechanisms might persist within social, political, and economic institutions in ways that lead to health disparities. Our finding of persistently higher emergency department visits due to asthma in redlined tracts compared with higher-graded tracts 80 years or more after the development and use of security maps, coupled with higher DEP emissions and poverty rates, might partly reflect a discriminatory legacy of redlining.

Our analysis had several limitations. The outcome variable, age-adjusted rates of emergency department visits due to asthma, is a proxy of asthma severity, control, and insufficient access to preventive services and, therefore, captures census tracts most burdened by asthma.[44] Health-care access, insurance coverage, and baseline asthma prevalence might be variable in redlined census tracts, leading to differential use of health care overall, and our findings might have under-estimated or over-estimated the true association. As we know, asthma prevalence is associated with neighbourhood deprivation and racial segregation, underlying our findings that census tracts previously redlined probably also have higher asthma prevalence than that of non-redlined tracts.[45] This warrants further investigation because targeted policies addressing redlining might have larger effects if they are also aimed at reducing overall asthma prevalence in high-burdened communities.

To limit our focus to the association between HOLC security map grades and rates of emergency department visits due to asthma, we excluded uncategorised census tracts. Jacoby and colleagues[9] found that adjusted violent crime rates in Philadelphia were highest in uncategorised neighbourhoods, suggesting an effect of noncategorisation that was possibly omitted by our analysis. However, this is unlikely because the mean asthma visit rates for excluded census tracts were between the mean rates of grade B and C census tracts (appendix p 1).

Given the amount of time between the creation of security maps and the rates of emergency department visits due to asthma in 2011–13, some or all our included confounders might be mediators of redlining and present-day health. When these potential mediators are excluded from our ordinary least squares and mixed models, HOLC risk grade estimates remained similar. Because previous socio-demographic factors such as 1940s demographics, housing quality, and median value of owner-occupied homes could confound our results, model coefficients might overestimate the true association.[9] Particularly, present-day housing quality is related to various asthma-associated exposures that are also more common in public housing, where lower-income people of colour are more likely to reside than white individuals, than in private housing and thus, might mediate or confound our findings.[35] Our exposure assessment strategy probably introduced some exposure classification bias, because we categorised census tracts into HOLC risk grades on the basis of the location of the centroid. Crossney and colleagues[46] developed a continuous metric for HOLC risk grade based on proportion of geographic area within each HOLC grade, offering a more nuanced way to capture the HOLC risk grades within present-day census tracts. We used HOLC categories to improve interpretation of the results. Additionally, figure 1 qualitatively shows minimal exposure misclassification when compared with original security maps. Other analytical limitations included scarce publicly available data on factors such as prevalence of smoking, which is associated with asthma, and other processes that could confound our results, such as ongoing gentrification.[47,48] Lastly, like all ecological analyses, our results are susceptible to ecological fallacy and residual confounding.

In our study, we found associations between government-sponsored, discriminatory redlining practices from the 1930s and present-day age-adjusted rates of emergency department visits due to asthma in eight major cities in California. Despite existing policies such as the Community Reinvestment Act that have funnelled billions of dollars into disadvantaged communities around the country, security maps drawn and colour-coded 80 years ago to designate perceived investment risk, partly on the basis of race, are associated with asthma health-care use in urban census tracts of California today. Future studies should attempt to incorporate individual-level data and additional covariates to better delineate this association.

References
1   Oh SS, White MJ, Gignoux CR, Burchard EG. Making precision medicine socially precise. Take a deep breath. *Am J Respir Crit Care Med* 2016; **193:** 348–50.
2   US Centers for Disease Control and Prevention. Asthma surveillance data. 2019. https://www.cdc.gov/asthma/most_recent_national_asthma_data.htm (accessed June 1, 2019).
3   Nardone A, Neophytou AM, Balmes J, Thakur N. Ambient air pollution and asthma-related outcomes in children of color of the USA: a scoping review of literature published between 2013 and 2017. *Curr Allergy Asthma Rep* 2018; **18:** 29.
4   Guarnieri M, Balmes JR. Outdoor air pollution and asthma. *Lancet* 2014; **383:** 1581–92.
5   Flores G, Snowden-Bridon C, Torres S, et al. Urban minority children with asthma: substantial morbidity, compromised quality and access to specialists, and the importance of poverty and specialty care. *J Asthma* 2009; **46:** 392–98.
6   Krishnan V, Diette GB, Rand CS, et al. Mortality in patients hospitalized for asthma exacerbations in the United States. *Am J Respir Crit Care Med* 2006; **174:** 633–38.
7   Canino G, McQuaid EL, Rand CS. Addressing asthma health disparities: a multilevel challenge. *J Allergy Clin Immunol* 2009; **123:** 1209–17.
8   Rothstein R. The color of law. New York: Liveright Publishing Corporation, 2017.
9   Jacoby SF, Dong B, Beard JH, Wiebe DJ, Morrison CN. The enduring impact of historical and structural racism on urban violence in Philadelphia. *Soc Sci Med* 2018; **199:** 87–95.
10 McClure E, Feinstein L, Cordoba E, et al. The legacy of redlining in the effect of foreclosures on Detroit residents' self-rated health. *Health Place* 2019; **55:** 9–19.
11 Mitchell B, Franco J. HOLC and "redlining" maps: the persistent structure of segregation and economic inequality. 2018. https://ncrc.org/holc/ (accessed Nov 4, 2019).
12 Jackson KT. Crabgrass frontier: the suburbanization of the United States. New York: Oxford University Press, 1985.
13 Michney TM, Winling L. New perspectives on new deal housing policy: explicating and mapping HOLC loans to African Americans. *J Urban Hist* 2019; published online Jan 9. DOI:10.1177/0096144218819429.
14 Aaronson D, Hartley D, Mazumder B. The effects of the 1930s "redlining" maps. 2019. https://www.chicagofed.org/publications/working-papers/2017/wp2017-12 (accessed June 7, 2019).
15 Krysan M, Crowder K. Cycle of segregation: social processes and residential stratification. New York: Russell Sage Foundation, 2017.
16 Gaskin DJ, Dinwiddie GY, Chan KS, McCleary RR. Residential segregation and the availability of primary care physicians. *Health Serv Res* 2012; **47:** 2353–76.
17 Kochhar R, Fry R. Wealth inequality has widened along racial, ethnic lines since end of Great Recession. Pew Research Center. 2014. https://www.pewresearch.org/fact-tank/2014/12/12/racial-wealth-gaps-great-recession/ (accessed May 28, 2019).

18 Chen E, Shalowitz MU, Story RE, et al. Parents' childhood socioeconomic circumstances are associated with their children's asthma outcomes. *J Allergy Clin Immunol* 2017; **140:** 828–35.

19 Nelson RK, Winling L, Marciano R, Connolly N, Ayers EL. Mapping inequality. American Panorama. https://dsl.richmond.edu/panorama/redlining (accessed March 13, 2018).

20 Californita Office of Environmental Health Hazard Assessment. CalEnviroScreen 3.0. 2018. https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30 (accessed April 19, 2019).

21 Rodriguez M, Zeise L. Update to the California Communities Environmental Health Screening Tool: CalEnviroScreen 3.0. 2017. https://oehha.ca.gov/media/downloads/calenviroscreen/report/ces3draftreportfinal.pdf (accessed June 1, 2019).

22 McCreanor J, Cullinan P, Nieuwenhuijsen MJ, et al. Respiratory effects of exposure to diesel traffic in persons with asthma. *N Engl J Med* 2007; **357:** 2348–58.

23 Brundson C, Chen H. GISTools: some further GIS capabilities for R. 2014. https://CRAN.R-project.org/package=GISTools (accessed June 4, 2019).

24 Oehlert GW. A Note on the delta method. *Am Stat* 1992; **46:** 27–29.

25 Bates D, Maechler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *J Stat Softw* 2015; **67:** 1–48.

26 Moran PAP. Notes on continuous stochastic phenomena. *Biometrika* 1950; **37:** 17.

27 Bivand RS, Pebesma E, Gomez-Rubio V. Applied spatial data analysis with R. New York: Springer-Verlag, 2013.

28 Huggins J. A cartographic perspective on the correlation between redlining and public health in Austin, Texas–1951. *Cityscape* 2017; **19:** 267–80.

29 Gee GC. A multilevel analysis of the relationship between institutional and individual racial discrimination and health status. *Am J Public Health* 2008; **98** (suppl 9)**:** S48–56.

30 Beyer KM, Zhou Y, Matthews K, Bemanian A, Laud PW, Nattinger AB. New spatially continuous indices of redlining and racial bias in mortgage lending: links to survival after breast cancer diagnosis and implications for health disparities research. *Health Place* 2016; **40:** 34–43.

31 Xie Y, Gough M. Ethnic enclaves and the earnings of immigrants. *Demography* 2011; **48:** 1293–315.

32 Kingsley SL, Eliot MN, Carlson L, et al. Proximity of US schools to major roadways: a nationwide assessment. *J Expo Sci Environ Epidemiol* 2014; **24:** 253–59.

33 Wright RJ. Health effects of socially toxic neighborhoods: the violence and urban asthma paradigm. *Clin Chest Med* 2006; **27:** 413–21.

34 Camacho-Rivera M, Kawachi I, Bennett GG, Subramanian SV. Associations of neighborhood concentrated poverty, neighborhood racial/ethnic composition, and indoor allergen exposures: a cross-sectional analysis of Los Angeles households, 2006–2008. *J Urban Health* 2014; **91:** 661–76.

35 Northridge J, Ramirez OF, Stingone JA, Claudio L. The role of housing type and housing quality in urban children with asthma. *J Urban Health* 2010; **87:** 211–24.

36 Morello-Frosch R, Lopez R. The riskscape and the color line: examining the role of segregation in environmental health disparities. *Environ Res* 2006; **102:** 181–96.

37 Jesdale BM, Morello-Frosch R, Cushing L. The racial/ethnic distribution of heat risk-related land cover in relation to residential segregation. *Environ Health Perspect* 2013; **121:** 811–17.

38 Casey JA, Morello-Frosch R, Mennitt DJ, Fristrup K, Ogburn EL, James P. Race/ethnicity, socioeconomic status, residential segregation, and spatial variation in noise exposure in the contiguous United States. *Environ Health Perspect* 2017; **125:** 077017.

39 Casey J, James P, Cushing L, Jesdale B, Morello-Frosch R. Race, ethnicity, income concentration and 10-year change in urban greenness in the United States. *Int J Environ Res Public Health* 2017; **14:** 1546.

40 Rao M, George LA, Rosenstiel TN, Shandas V, Dinno A. Assessing the relationship among urban trees, nitrogen dioxide, and respiratory health. *Environ Pollut* 2014; **194:** 96–104.

41 Mehdipanah R, Ramirez J, Abedin S, F Brown S. Housing discrimination and health: understanding potential linking pathways using a mixed-methods approach. *Soc Sci* 2018; **7:** 194.

42 Kramer MR, Black NC, Matthews SA, James SA. Population health: the legacy of slavery and contemporary declines in heart disease mortality in the US south. *SSM-Popul Health* 2017; **3:** 609–17.

43 Esenwa C, Ilunga Tshiswaka D, Gebregziabher M, Ovbiagele B. Historical slavery and modern-day stroke mortality in the United States stroke belt. *Stroke* 2018; **49:** 465–69.

44 Dougherty RH, Fahy JV. Acute exacerbations of asthma: epidemiology, biology and the exacerbation-prone phenotype. *Clin Exp Allergy* 2009; **39:** 193–202.

45 Simons E, Dell SD, Moineddin R, To T. Neighborhood material deprivation is associated with childhood asthma development: analysis of prospective administrative data. *Can Respir J* 2019; **2019:** 1–7.

46 Crossney KB, Bartelt DW. The legacy of the Home Owners' Loan Corporation. *Hous Policy Debate* 2005; **16:** 547–74.

47 Althuis MD, Sexton M, Prybylski D. Cigarette smoking and asthma symptom severity among adult asthmatics. *J Asthma* 1999; **36:** 257–64.

48 Badger E, Bui Q, Gebeloff R. The neighborhood is mostly black. The home buyers are mostly white. *The New York Times,* April 27, 2019.