Title

Mapping Climate Change Exposures, Vulnerabilities, and Adaptation to Public Health Risks in the San Francisco Bay and Fresno Regions

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MAPPING CLIMATE CHANGE EXPOSURES, VULNERABILITIES, AND ADAPTATION TO PUBLIC HEALTH RISKS IN THE SAN FRANCISCO BAY AND FRESNO REGIONS

A White Paper from the California Energy Commission's California Climate Change Center

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DISCLAIMER

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PREFACE

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the California Climate Change Center to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions.

For more information on the PIER Program, please visit the Energy Commission's website http://www.energy.ca.gov/research/index.html or contract the Energy Commission at (916) 327-1551.

ABSTRACT

This study reviewed first available frameworks for climate change adaptation in the public health arena. The authors propose a conceptual framework with a three-step procedure to assess climate change vulnerabilities.

First, the study team identified and modeled heat stress, environmental, social, and health factors that are closely related to climate change and vulnerability. Second, the team quantified the cumulative impacts of four high-priority factors at regional level using the cumulative environmental hazard inequality index. Third, the team applied the environmental justice screening tool to map the four high-priority factors to identify areas with increased vulnerability to the health impacts of climate change.

In addition to the heat stress estimated using air monitoring data, the team applied satellite data to create models of the land surface temperature at 30-meter resolution and provided a measure of small-scale variations in the urban heat island.

Regionally, based on the cumulative environmental hazard inequality index, adaptive capacity had the greatest cumulative inequality in both the San Francisco Bay Area and Fresno regions, and those inequalities were largely contributed by inequalities from tree canopy shading. Social and health vulnerability had the second largest cumulative inequality in both regions. Lack of car ownership was the major impact in creating such inequalities. Air pollution inequality came third, based on the main pollutants in both regions, and this was mainly contributed by inequalities from diesel particulate matter exposure. By contrast, cumulative inequalities in heat stress were the least. However, heat stress inequality was still significant different from the equality line.

Locally, based on the environmental justice screening tool, downtown urban areas for both Fresno County and the San Francisco Bay Area showed cumulatively higher vulnerability than more outlying areas, with the exception of the rural western portion of Fresno County. The cumulative inequalities calculated by the cumulative environmental hazard inequality index and the environmental justice screening method can be a useful tool for highlighting areas of greatest vulnerability for targeting adaptation planning.

Keywords: climate change; heat stress; cumulative environmental inequality index; environmental justice screening tool; vulnerability

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TABLE OF CONTENTS

Introduction ... 1

Section 1: Frameworks for the Conceptualization of Links between Climate Change and Health: A Review ... 1

Health Outcomes Associated with Climate Change ... 1

Climate Change and Health Impacts: The IPCC (AR4) Framework ... 2

The Public Health Approach ... 3

Geographies of Environmental Health Risk ... 5

Climate Change Adaptation Scenarios ... 6

Social Vulnerability to Environmental Hazards ... 8

Indicators of Cumulative Environmental Exposures in California ... 9

A California-specific Framework to Estimate Heat-Associated Mortality and Morbidity ... 11

Intrinsic Risk Factors ... 11

Extrinsic Risk Factors ... 11

Synthesis Commentary on Frameworks ... 14

Section 2: Empirical Studies in the San Francisco Bay and Fresno Regions ... 14

Modeling and Mapping Environmental, Social, and Health Factors Related to Climate Change and Vulnerability: Step I ... 15

Modeling Air Conditioning Usage Prevalence ... 16

Modeling Air Pollution ... 18

Adverse Birth Outcomes ... 23

Elderly Living Alone and Household Car Access ... 23

Modeling Summer Heat Stress Using Weather Monitoring Data ... 23

Impervious Surface and Tree Canopy Cover from NLCD ... 28

Race-ethnicity and Socioeconomic Status from the U.S. Census ... 28

Quantifying Regional Environmental Inequalities with Exposure to Single and Cumulative Environmental Hazards: Step II ... 35

Cumulative Inequality Indices 35
Inequalities in Heat Stress 36
Inequalities in Air Pollution 36
Inequalities in Social and Health Vulnerability 38
Inequalities in Climate Change Adaptive Capacity 39
Cumulative Inequalities of the Four Impacts 40
Identifying Within-Region Environmental Inequalities with Exposure to Cumulative Environmental Hazards: Step III 41
EJ Screening Results 41
Future Directions for Vulnerability Analyses 54
Modeling Summer Heat Stress Using Land Surface Temperature 55
Section 3: Conclusions 65
References 67
Glossary 72
Appendix A: Review of Peer-Reviewed Research, Government Documents and Grey Literature on Climate Change in California 74
Government Reports: Summary 78
Who is working on Climate Change? 78
California Climate Change Adaptation and Executive Order S-13-08 by the California Governor 79
California Climate Action Team 79
The Climate Change Adaptation Report General Framework 80
Climate Change Simulation 80
The Climate Scenarios 80
California Climate Change Scenarios and Models 81
The Joint Policy Committee: Regional Agency Adaptation Program 85
Proposed Climate Change Bay Plan Amendment 86
Planning for Climate Change: Resources for Bay Area Local Government 86
Mapping Areas Vulnerable to Sea Level Rise 87
Delta Alliance Partnership 88

Rising Tides Design Competition 88
Federal Agencies 88
San Francisco Bay Area Projections and Adaptation 88
Resources for California........ 89
California Climate Adaptation Strategy........ 89
Key Recommendations from the 2009 California Climate Adaptation Strategy........ 91
Resources for the San Francisco Bay Area 92

LIST OF FIGURES

Figure 1: Potential Health Effects of Climate Variability and Change 2

Figure 2: IPCC Schematic Diagram of Pathways by Which Climate Change Affects Health, and Concurrent Direct-acting and Modifying (Conditioning) Influences of Environmental, Social, and Health-system Factors 3

Figure 3. Extended Conceptual Framework for Spatial Analysis in Epidemiology and Public Health 5

Figure 4. Application of Conurbation-scale Risk Assessment 6

Figure 5. Using Conurbation-scale Risk Assessment to Analyze Heat Stress Risk 8

Figure 6. The Heat Vulnerability Index 9

Figure 7. Positive and Negative Inequality Curves. A positive curve indicates census tracts with a higher percentage of a specific racial-ethnic group or lower socioeconomic position have lower shares of environmental hazard. The negative curve portrays the opposite case. The equality line indicates that there is no environmental inequality for the exposure across racial-ethnic or socioeconomic composition measures 10

Figure 8. Land Cover Characteristics Across Comparable Neighborhood Poverty Groups in California Urban Areas 12

Figure 9. Land Cover Characteristics Across Comparable Neighborhood Racial/Ethnic Minority Groups in California Urban Areas 12

Figure 10. Analysis Framework in Exposure Inequalities of Climate Change 15

Figure 11. Modeled San Francisco Bay Area (a) and Fresno Region (b) Air Conditioning Usage Prevalence from the 2009 Residential Appliance Saturation Survey 17

Figure 12. Modeled NO_2 Concentrations Predicted at the Census Tract Level for (a) San Francisco Bay Area and (b) the Fresno Region County 20

Figure 13. Modeled $PM_{2.5}$ Concentrations Predicted at the Census Tract Level for (a) San Francisco Bay Area and (b) Fresno County 21

Figure 14. Modeled Diesel PM Concentrations Predicted at the Census Tract Level for (a) San Francisco Bay Area and (b) Fresno County 22

Figure 15. San Francisco Bay Area (a) and Fresno (b) Percent of Live Births That Are Preterm or Low Birth Weight 24

Figure 16. San Francisco Bay Area (a) and Fresno (b) Population Over 65 Who Live Alone 25

Figure 17. San Francisco Bay Area (a) and Fresno (b) Proportion of Households Without a Car 26

Figure 18. San Francisco Bay Area Heat Stress for Daily (a) Absolute and (b) Relative Temperature Exceedance (°C per day) 29

Figure 19. Fresno Region Heat Stress Indices for Daily (a) Absolute and (b) Relative Temperature Exceedance (°C per day) 30

Figure 20. San Francisco Bay Area (a) and Fresno (b) Tree Canopy Cover from the National Land Cover Database 2001 31

Figure 21. San Francisco Bay Area (a) and Fresno (b) Impervious Surface Cover from the National Land Cover Database 2001 32

Figure 22. San Francisco Bay Area (a) and Fresno Region (b) Race-ethnicity Composition from the 2000 U.S. Census 33

Figure 23. San Francisco Bay Area (a) and Fresno Region (b) Poverty Status from the 2000 U.S. Census 34

Figure 24. Single and Cumulative Inequalities in Heat Stress for the San Francisco Bay Area (upper) and the Fresno region (lower) Based on Race-ethnicity (left) and Poverty Status (right). 36

Figure 25. Single and Cumulative Inequalities in Air Pollution for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right) 37

Figure 26. Single and Cumulative Inequalities in Social Vulnerability for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right). 38

Figure 27. Single and Cumulative Inequalities in Climate Change Adaptation for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right) 39

Figure 28. Cumulative Inequalities in Considering all the Four Aspects of Impacts for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right) 40

Figure 29a. Quintile Heat Stress Vulnerability Scores at the Census Tract Level in the San Francisco Bay Area 43

Figure 29b. Air Pollution Quintile Scores at the Census Tract Level in the San Francisco Bay Area 44

Figure 29c. Social and Health Quintile Scores at the Tract Level in the San Francisco Bay Area. 45

Figure 29d. Lack of Climate Change Adaptive Capacity Quintile Scores at the Census Tract Level in the San Francisco Bay Area 46

Figure 29e. Cumulative Quintile Scores at the Census Tract Level in the San Francisco Bay Area 47

Figure 30a. Heat Stress Quintile Scores at the Census Tract Level in Fresno County 49

Figure 30b. Air Pollution Quintile Scores at the Census Tract Level in Fresno County 50

Figure 30c. Social and Health Quintile Scores at the Census Tract Level in Fresno County 51

Figure 30d. Lack of Climate Change Adaptive Capacity Quintile Scores at the Census Tract Level in Fresno County 52

Figure 30e. Cumulative Quintile Scores at the Census Tract Level in Fresno County 53

Figure 31. San Francisco Bay Area Land Cover Types Based on Landsat Classification 56

Figure 32. San Francisco Bay Area Land Surface Temperature by Our Research Team Using Landsat TM Data 59

Figure 33. San Francisco Bay Area Land Surface Temperature Based on the 2006 California Pacific Coast Land Cover Classification 60

Figure 34. City of Fresno Land Surface Temperature Based on the 2005 Central Valley Land Cover Classification 61

Figure 35. San Francisco Bay Area Surface Emissivities Based on ASTER Data 63

Figure 36. San Francisco Bay Area Surface Temperature Based on NASA Emissivities 64

LIST OF TABLES

Table 1. Climate Change Examples for Each Public Health Service Designed by Frumkin et al. 2008 4

Table 2. Proportion of Households without Access to Any Air Conditioning by Race and SES, for the Los Angeles-Long Beach Metropolitan Area, California (2003)* 13

Table 3. Data Sources Used to Estimate Environmental, Social, and Health Risks Related to Climate Change and Vulnerability 16

Table 4. Model of Heat Stress in Daily Absolute Temperature Exceedance for the State of California Using 123 Monitoring Stations for 2001–2005* 27

Introduction

Human-induced climate change is a well-documented phenomenon that continues to affect ecosystems and human health. In North America, these changes include less extreme winters in northern cities, increased frequency of heat waves and wildfires, expanded ranges for vector- and tick-borne diseases, and increased air pollution (IPCC 2007a). Each of these factors is relevant to public health and must be considered in the planning and implementation of climate change adaptation strategies.

In California, climate change as well as many mitigation policies aimed to attenuate its effects may exert a disproportionate burden on lower socioeconomic status (SES) communities (Shonkoff et al. 2009). By taking into consideration both vulnerability and exposure impacts, this study assessed where climate change adaptation efforts are most needed on geographic and social bases.

The paper is divided into two main sections: (1) a literature review on available frameworks for climate change adaptation in the public health arena, and (2) a conceptual framework based on this literature review, using a three-step procedure to assess vulnerabilities and exposures in the San Francisco Bay and Fresno regions.

Section 1: Frameworks for the Conceptualization of Links between Climate Change and Health: A Review

To analyze public health impacts of climate change, it is necessary to have a specific framework to guide the process. A literature review was conducted, which demonstrated that a variety of methods have been proposed as frameworks for hazard assessment of climate change.

Health Outcomes Associated with Climate Change

Haines and Patz (2004) proposed a framework to assess climate change impacts based on health outcomes from various climatic shifts. This framework is summarized in Figure 1. The authors highlight increased intensity and frequency of floods, droughts, and extreme weather events; elevated air pollution and aeroallergens; and increased incidence of infectious diseases, thermal stress, and malnutrition as possible consequences of climate change.

Though the authors take into account both population exposures and adaptation measures that could limit health effects, the framework lacks an assessment of either individual-level or community-level vulnerabilities, without which it is difficult to quantify risk. Vulnerability is briefly mentioned in the discussion of floods, where the authors point out that there will be a greater impact on developing countries due to a lack of public health infrastructure and high rates of habitation in high-risk flood-prone areas such as flood plains. Intra-national variability in vulnerability, however, was not discussed.

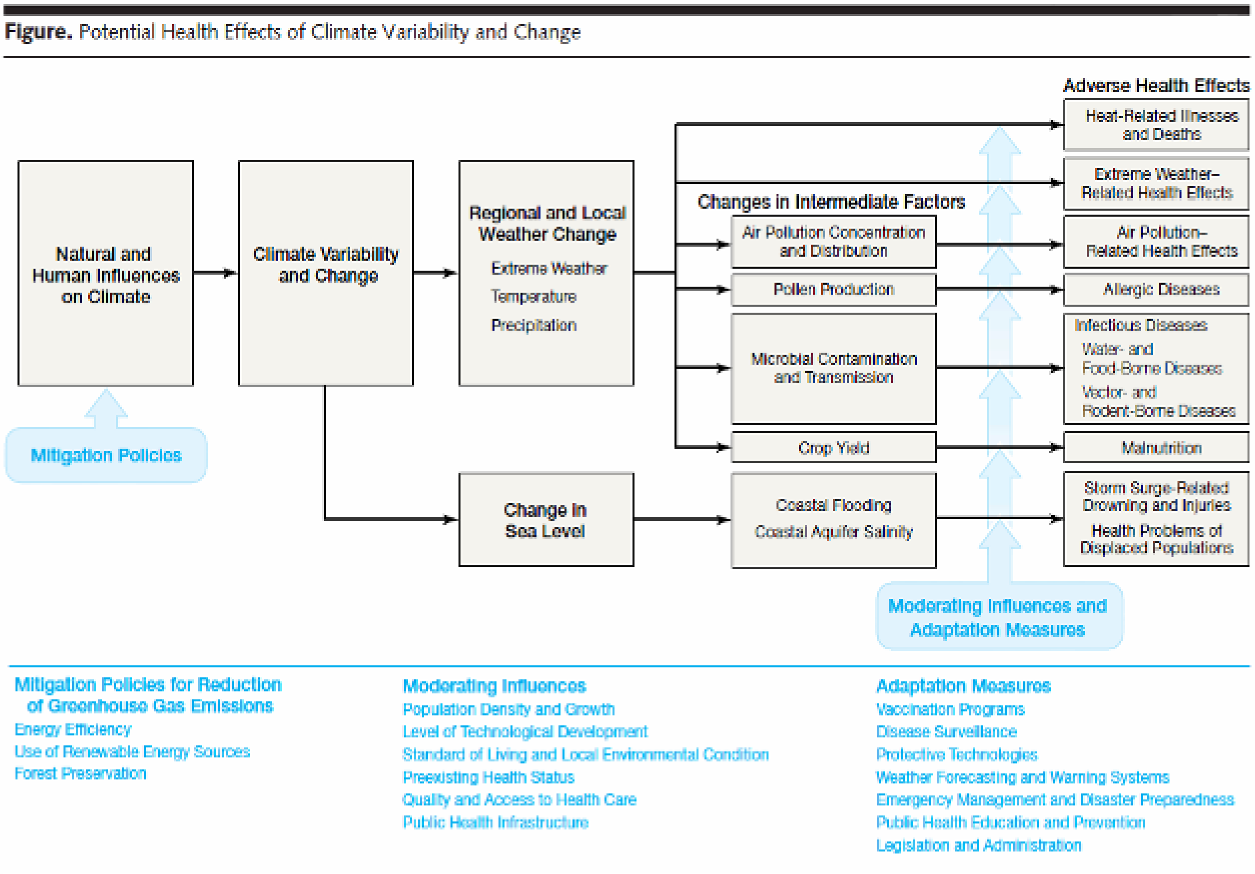


Figure 1: Potential Health Effects of Climate Variability and Change

Source: Haines and Patz 2004

Climate Change and Health Impacts: The IPCC (AR4) Framework

The Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report (AR4) formed a framework that relates pathways between physical climatic shifts (i.e., changing weather patterns and their consequences) and direct human health outcomes. This is a modification of the framework put forth by Haines and Patz. Health impacts associated with climate change are caused by direct and indirect exposures to climate, modifications of environmental and societal conditions by climatic shifts, and feedback loops amongst these factors. As Figure 2, developed by the IPCC, demonstrates, climate change leads to health consequences through pathways of direct exposures (e.g., extreme heat), indirect exposures (e.g., changes in water, air, and food quality), and social and economic disruptions. Thus, climate change produces a dynamic system where a change in one condition exerts influence in multiple pathways with associated health consequences. Although the IPCC report does address adaptation and vulnerability in its discussion of health and climate change, and this figure shows how modifying influences can affect the direct and indirect links between exposures that are directly and indirectly related to climate change, the figure itself does not specify how adaptation measures could intervene between climate change and exposures, or between exposures and health outcomes, as does the figure by Haines and Patz. Nor does Figure 2 address vulnerability.

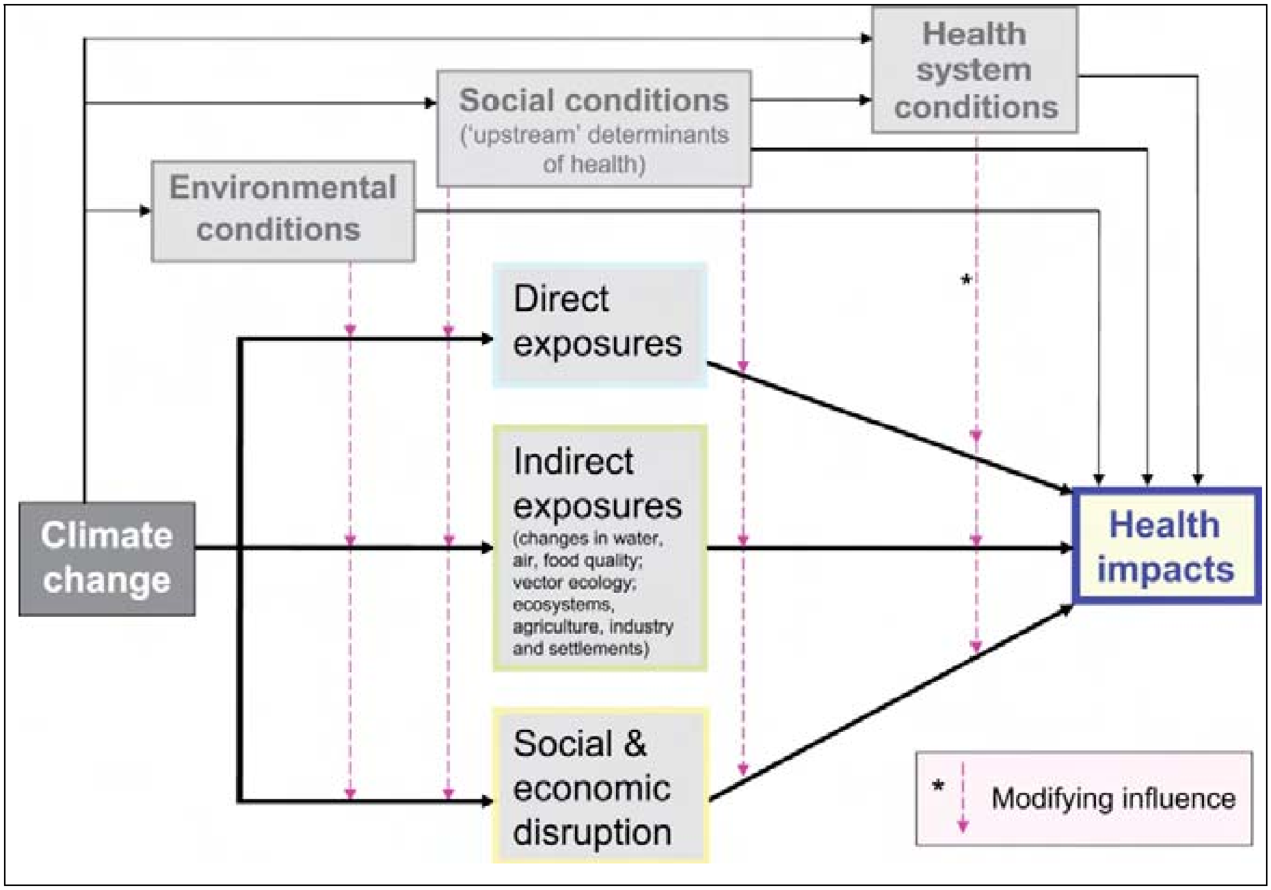


Figure 2: IPCC Schematic Diagram of Pathways by Which Climate Change Affects Health, and Concurrent Direct-acting and Modifying (Conditioning) Influences of Environmental, Social, and Health-system Factors

Source: IPCC 2007a, p. 47

The Public Health Approach

Some research has focused specifically on general public health implications associated with climate change. One such study (Frumkin et al. 2008) summarizes the projected impacts of climate change on health in the United States. To inform policymakers and public health officials, the authors propose a framework for a "public health approach to climate change." In 1994, the American Public Health Association worked with federal, state, and local agencies to create a list of "10 Essential Services of Public Health," which Frumkin et al. (2008) then interpreted within the context of climate change (see Table 1).

Table 1. Climate Change Examples for Each Public Health Service Designed by Frumkin et al. 2008

Service	Climate Change Example
1. Monitor health status to identify and solve community health problems.	Tracking of diseases and trends related to climate change
2. Diagnose and investigate health problems and health hazards in the community.	Investigation of infectious water-, food-, and vector-borne disease outbreaks
3. Inform, educate, and empower people about health issues.	Informing the public and policymakers about health impacts of climate change
4. Mobilize community partnerships and action to identify and solve health problems.	Public health partnerships with industry, other professional groups, faith community, and others, to craft and implement solutions
5. Develop policies and plans that support individual and community health efforts.	Municipal heat-wave preparedness plans
6. Enforce laws and regulations that protect health and ensure safety.	(Little role for public health)
7. Link people to needed personal health services and ensure the provision of health care when otherwise unavailable.	Health care service provision following disasters
8. Ensure competent public and personal health care workforce.	Training of health care providers on health aspects of climate change
9. Evaluate effectiveness, accessibility, and quality of personal and population-based health services.	Program assessment of preparedness efforts such as heat-wave plans
10. Research for new insights and innovative solutions to health problems.	Research on health effects of climate change, including innovative techniques such as modeling, and research on optimal adaptation strategies

For example, for the first service ("monitor health status to identify and solve community health problems"), the authors point out the necessity of collecting data from multiple categories, including environmental risk, vulnerability, and disease. Though these data are often collected on different spatial scales, they must be integrated for useful surveillance to occur such that early warning systems will effectively identify areas that are most in need of intervention. This service, along with service 10 ("research for new insights and innovative solutions to health problems") are the two most salient points for our future analysis. Many of the other services are more geared toward policymakers and outreach groups; whereas, for our research we plan to focus on identifying significant factors affecting greater inequality from climate change and investigating areas that will be most affected by climate change and the techniques that can contribute most to adaptation strategies.

Geographies of Environmental Health Risk

In 2009, Jerrett and colleagues published a chapter (Jerrett et al. 2009) that proposed translating Mayer's conceptualization of health and place (Mayer 1983) into an operational framework that includes three underlying geographies: exposure, susceptibility, and adaptation. Many health geographers explore only one of these domains at a time, yet others seek to understand areas of maximal overlap where two or more domains converge (see Figure 3). For climate change studies in particular, it is necessary to take into account this three-domain overlap.

Figure 3. Extended Conceptual Framework for Spatial Analysis in Epidemiology and Public Health

Adapted from Jerrett et al. 2009

Thus, our analytical framework proposed in 2009 (Jerrett et al. 2009) hinged on four related concepts: (1) geography of susceptibility; (2) geography of exposure; (3) geography of adaptation, and (4) points of intersection between these three, which they refer to as the *geography of risk.* The authors discussed how each concept encompasses many factors, such as meteorological dispersion of pollutants, time-space human activity patterns, behavioral changes in relation to perceived or real danger, and distributions of susceptible populations and individuals in time and space.

It should also be noted that there are other frameworks in the literature that are similar to the geography of risk framework. For example, the field of environmental health geography often focuses on understanding the overlap of two or more of these spheres of influence. Additionally, Working Group II for the Fourth Assessment Report for the IPCC defines vulnerability to climate change as a function of a system's exposure, sensitivity, and adaptive capacity (IPCC 2007b). Thus the domains of geography and of climate change impacts and adaptation arrived at essentially the same framework for identifying vulnerable communities.

Climate Change Adaptation Scenarios

Lindley et al. (2006) applied conurbation-scale risk and adaptation assessment methods to study the response of the greater Manchester urban area to climate change (Lindley et al. 2006). This new, explicitly spatial method was developed to address the type of information needed to plan adaptation to climate change.

Conurbation-scale risk assessment was performed to evaluate an entire urban-system as well as to provide a basis for neighborhood-level analyses. Similar to the conceptual framework introduced earlier, the authors defined risk to be an interaction between hazard, exposure, and vulnerability. This methodology uses geographic information systems (GIS) to create maps of various risk elements (i.e., population), hazards (i.e., maximum August temperatures), and the urban-system (i.e., urban morphology types). A layer that maps the current vulnerability of the region is then created by merging the risk element layers to the urban-system layer, and a layer that projects future exposure is created by merging the hazard layer to the urban-system layer. Finally, the projected exposure layer and current vulnerability layer are merged to create a final risk layer (see Figure 4).

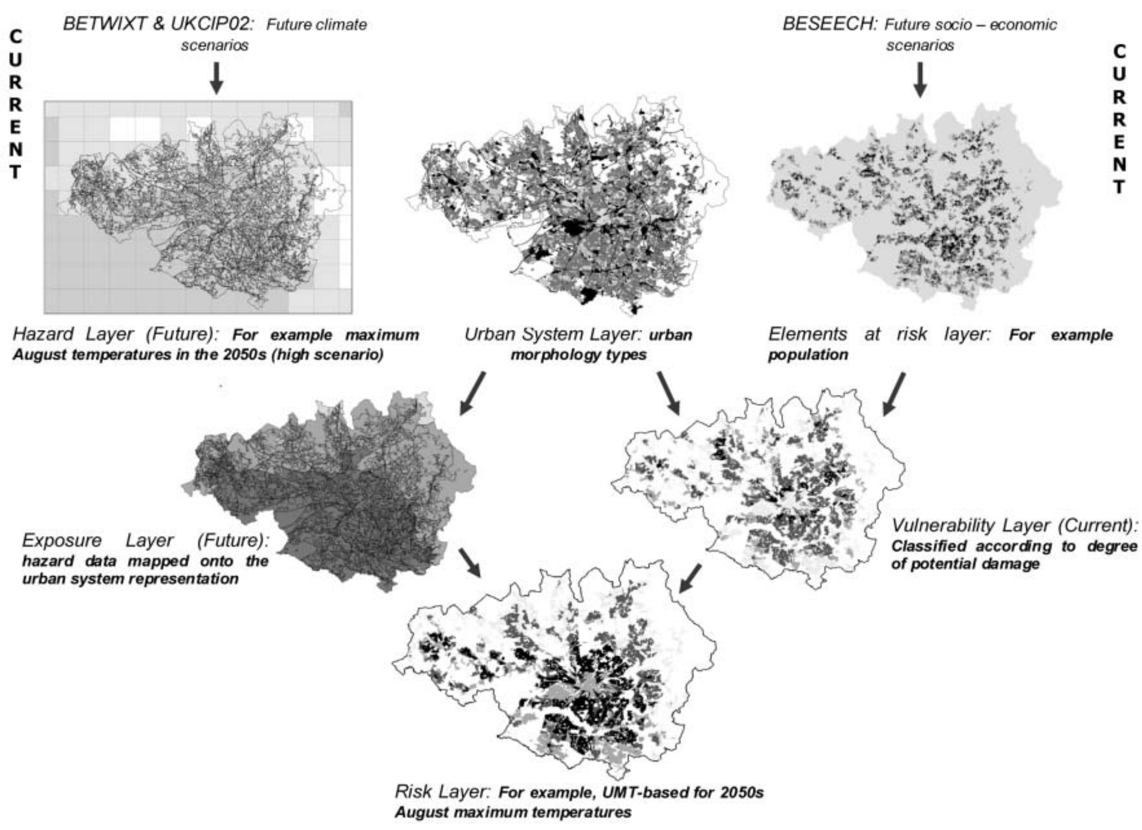


Figure 4. Application of Conurbation-scale Risk Assessment

Source: Lindley et al. 2006

The authors reported this methodology to be valuable for several reasons. First, since each risk element is represented as a separate layer, it is possible to modify each element individually to reassess the final risk layer. This approach allows planners to easily evaluate different adaptation strategies to determine how best to mitigate the risk faced by urban areas due to climate change. Second, by developing this GIS method, it is possible to not only identify current areas where adaptation is most necessary in terms of the risks posed by climate change, but it is also possible to identify areas that are most at risk in the future. Finally, to perform the conurbation-scale risk assessment, the authors used previously generated data to create the various GIS layers. By utilizing available data, it is possible to produce results rapidly. Rapid analytical tools are increasingly important for urban areas to swiftly adapt to climate change.

Further, this framework specifies the ways in which conurbation-scale risk assessment can be used to affect policy, as demonstrated by Rayner and Malone (1998), who outline "the ten principles for improved climate policy" and detail how this new method fulfills each of the principles (Rayner and Malone 1998). For example, in response to the principle that states that it is necessary to "realize that there are institutional as well as environmental limits to sustainability" (principle number two), the authors point out that the conurbation-scale risk assessment allows for a wide array of information from various agencies to be taken into account. Through systematically addressing these principles, conurbation-scale risk assessment proves to be a useful tool for planning adaptation strategies.

To demonstrate the method, the authors analyze how socioeconomic change affects the risk of heat stress (see Figure 5). This case study led the authors to make several policy suggestions that could help to mitigate overall heat stress risk in the Greater Manchester area, United Kingdom (UK). To increase an individual's personal adaptive capacity, the authors propose longer working lives to provide health coverage and to create stronger social networks. Additionally, the authors recommend increasing urban density and access to improved transport systems so that the region can grow with less social deprivation. Finally, the authors encourage increased green space to reduce the heat hazard.

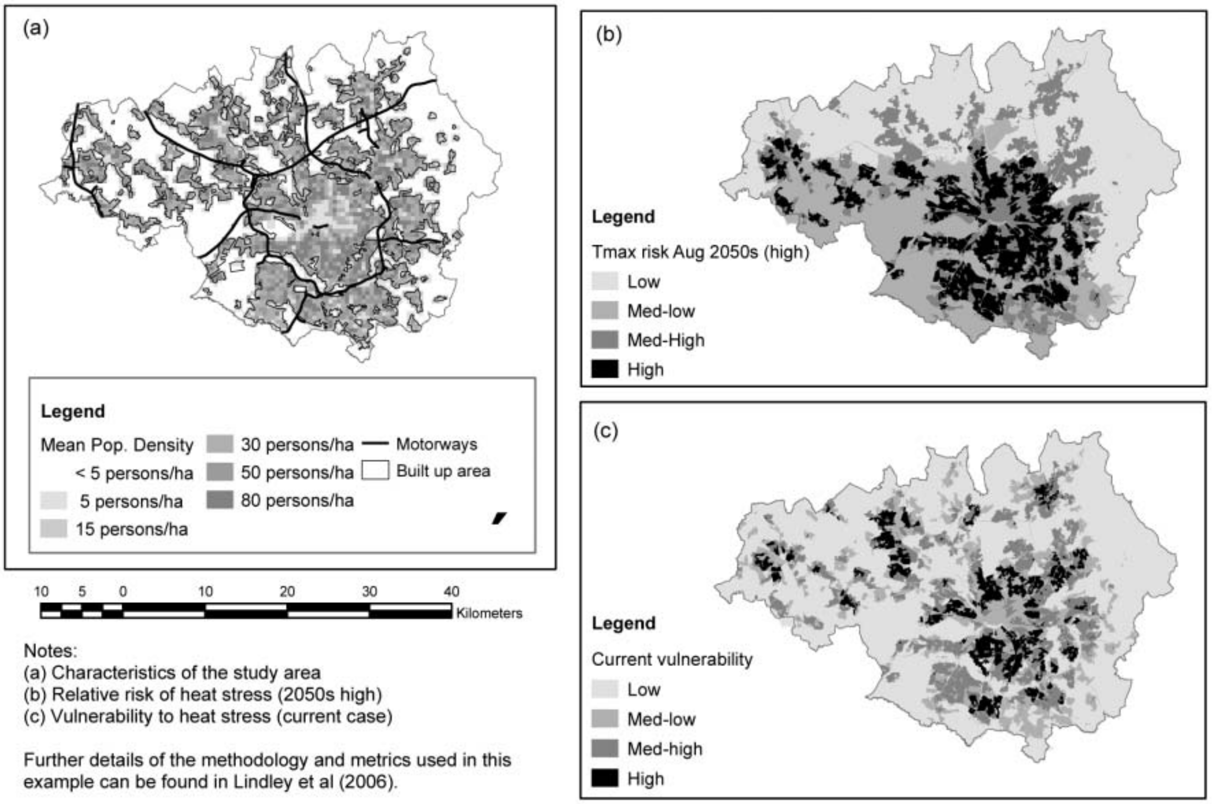


Figure 5. Using Conurbation-scale Risk Assessment to Analyze Heat Stress Risk

Source: Lindley et al. 2006

In addition to the usefulness of visualization and cartographic overlay, conurbation-scale risk assessment can be completed relatively quickly because it utilizes the best available spatial data rather than creating new data. It also allows researchers to easily compare various risk scenarios in order to discern which adaptive approach to climate change is most appropriate.

Social Vulnerability to Environmental Hazards

A construct similar to the geography of risk was conceptualized by Cutter et al. 2003 in which social vulnerability and biophysical vulnerability combine to affect risk geographically. The authors conceptualize social vulnerability as being a combination of an exposure model of the hazard, the social construct of vulnerability in the extent to which a society is resilient to (or less susceptible to) a hazard, and how the exposures and susceptibilities combine geographically. The Social Vulnerability Index (SoVI) was created in a way similar to the conurbation-scale model of overlaying vulnerability layers, except that it took into account the collinearity of many of the vulnerability variables and used a factor analysis to reduce 42 vulnerability variables to 11 independent factors of vulnerability that were then summed to create the SoVI.

This methodology was implemented by Reid et al. (2009) to create a national heat vulnerability index (HVI). The index combined ten variables that had been previously found in the epidemiological literature to increase risk of morbidity or mortality during extreme heat events. A factor analysis created four independent factors of vulnerability that represented (1) social and environmental vulnerability, (2) social isolation, (3) air conditioning prevalence, and (4) pre-existing health conditions. These four factors were summed at the census tract level to obtain the HVI that was then mapped for almost 40,000 census tracts across the United States. The map (Figure 6) demonstrated varying vulnerability to heat events nationally, with higher vulnerability along the Pacific Coast, in the Northeast and the Upper Midwest, but also there was evidence of differential heat vulnerability in metropolitan areas with higher vulnerability in the downtown areas than in the surrounding suburban areas.

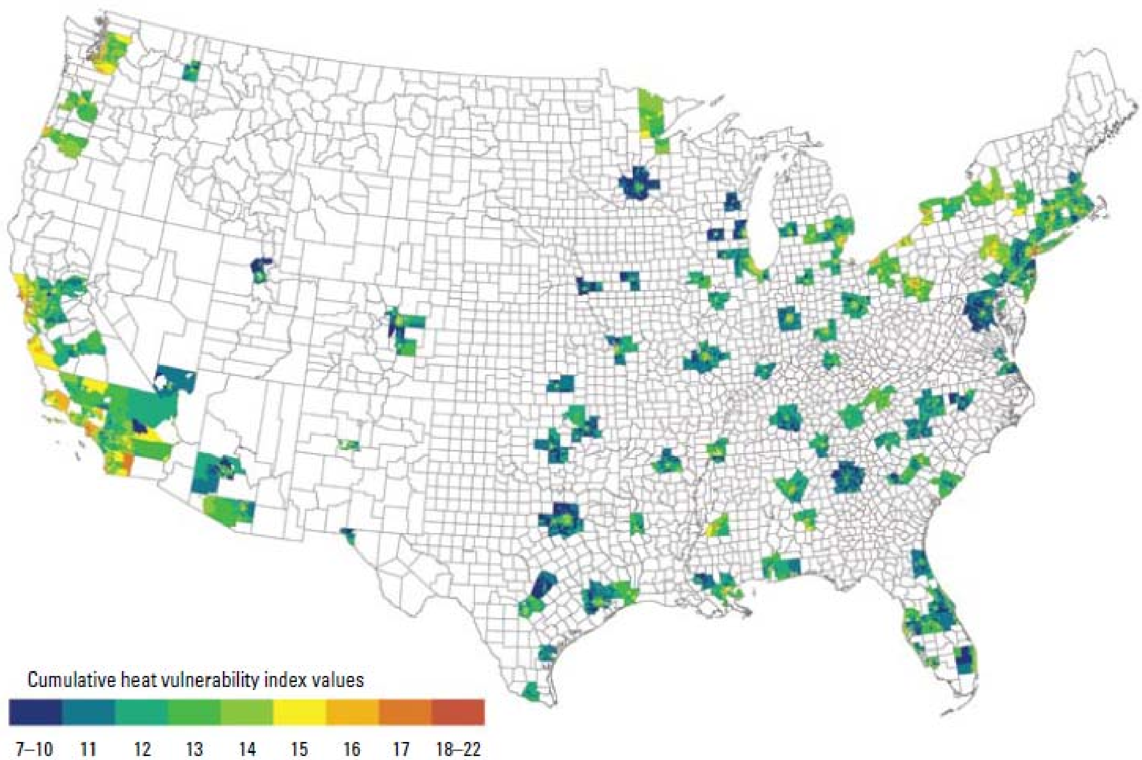


Figure 6. The Heat Vulnerability Index

Source: Reid et al. 2009

Indicators of Cumulative Environmental Exposures in California

Su et al. (2009) developed an indicator that can be used to track inequalities in exposures among different social groups and can estimate the effects of single or multiple (cumulative) environmental exposures. The authors modified a "concentration index" measure that is commonly used in the fields of social science and health planning (O'Donnell et al. 2008) and extended to summarize inequality in the distribution of multiple environmental hazards (Figure 7). A summary measure of inequality is defined as twice the area between an inequality curve and the equality line. This measure gives a quantitative summary of inequality among groups, in which 0 indicates that all groups, or in our case all census tracts, have an equal share of environmental burden (i.e., no inequality), and 1 is the highest level of inequality, where one group or one census tract bears whole detrimental burden.

Such an index only captures inequalities associated with single factors. To measure the socioeconomic or racial-ethnic inequalities from multiple burdens, we calculated the cumulative environmental hazard inequality index (CEHII) (Su et al. 2009). The index uses the cumulative proportion of the population—ranked by area-based racial-ethnic composition or socioeconomic strata, starting from the most disadvantaged—against cumulative environmental hazard burdens. We assumed the existence of fully multiplicative burdens (i.e., every pollutant was multiplicatively synergistic with every other pollutants). This methodological approach integrates multiple burdens and social data into a single index. This is akin to combining the hazard layer and vulnerability layer as per the method presented by Lindley et al. (2006), but executed more quantitatively. The authors then applied the index to Los Angeles, California, to determine whether inequalities exist for exposure to particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), nitrogen dioxide (NO_2), and diesel PM. Socioeconomic variables and environmental hazards were then combined into two separate models, one additive and one multiplicative, to compute the combined environmental impact. It was found that there are slight but significant inequalities for environmental exposures. In addition to the application results, Su et al. (2009) present a quantitative approach for assessing environmental hazards, which could be applied to climate change studies.

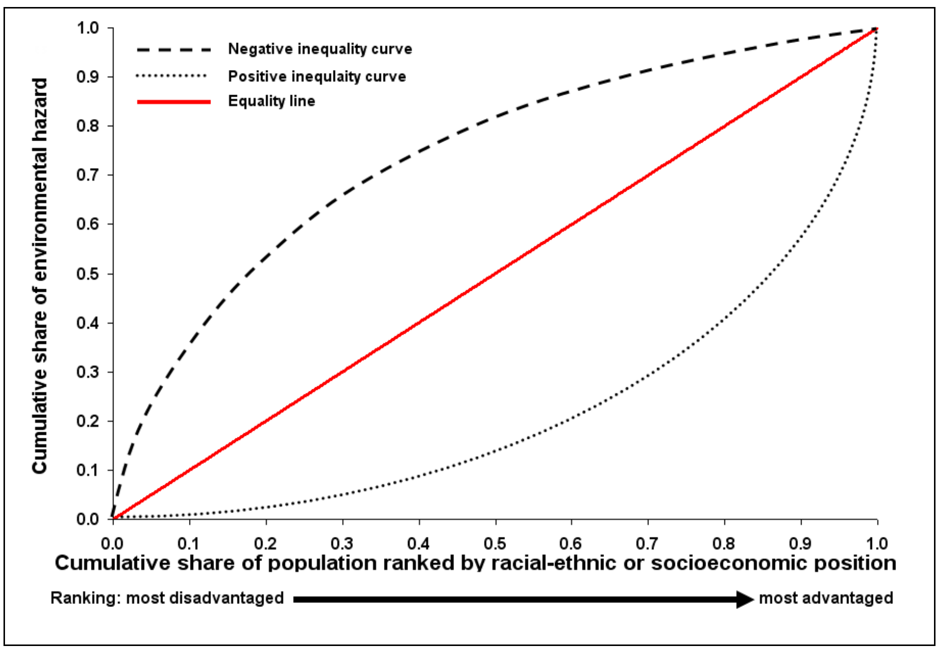


Figure 7. Positive and Negative Inequality Curves. A positive curve indicates census tracts with a higher percentage of a specific racial-ethnic group or lower socioeconomic position have lower shares of environmental hazard. The negative curve portrays the opposite case. The equality line indicates that there is no environmental inequality for the exposure across racial-ethnic or socioeconomic composition measures.

Source: Su et al. 2009

A California-specific Framework to Estimate Heat-Associated Mortality and Morbidity

Although heat exposure alone is implicated in increased morbidity and mortality, physiological, social, and economic factors are also fundamental to understanding the uneven distribution of these adverse heat-specific health outcomes across diverse populations (Cutter et al. 2003). Shonkoff et al. (2009) developed a categorization scheme and framework to assess vulnerability to heat-associated morbidity and mortality outcomes: Risk factors for heat-associated mortality and morbidity can be categorized as either intrinsic (i.e., age, disability, medical status) or extrinsic (e.g., housing, access to cooling centers, transportation). They also found that low SES groups are disparately affected by both of these risk categories and are thus at a decreased advantage as climate change increases the intensity and frequency of heat events.

Intrinsic Risk Factors

In terms of intrinsic factors, people suffering from chronic medical conditions have an elevated risk of death during heat waves (Kilbourne 1997; Kovats and Hajat 2008) compared with those that are healthy. In fact, a study on the heat-specific mortality during the 2003 heat wave in France reported that over 70 percent of those who died at home had pre-existing medical conditions, particularly cardiovascular and/or psychological illnesses (Poumadere et al. 2005). Because low SES groups are disproportionately affected by medical conditions partially due to their lack of access to technological, informational, and social resources to cope with these conditions (Phelan et al. 2004), they tend to be most adversely affected by extreme heat events. Epidemiologic studies of heat-associated mortality show an increased risk among those older than ~50 years of age (Kovats and Jajat 2008), lending evidence to the assertion that older age is also an intrinsic risk factor.

Extrinsic Risk Factors

In terms of extrinsic risk factors, low-income urban communities and communities of color are particularly vulnerable to increased frequency of heat waves and higher temperatures because they are often segregated in the inner city (Schulz et al. 2002; Williams and Collins 2001), which is more likely to experience "heat-island" effects (Harlan et al. 2008). Heat-islands occur in urban areas when lighter-colored (higher albedo) materials such as grass, trees, and soil are replaced by darker-colored (lower albedo) materials such as roads, buildings, and other surfaces, leading to increased absorption of sunlight. This increased absorption of sunlight decreases the dissipation of heat, thus warming the local area (Oke 1973). A recent land cover analysis (Shonkoff et al. 2009) shows a positive relationship between the proportion of impervious land cover in neighborhoods and an increasing proportion of residents living in poverty, as well as a negative relationship between the amount of tree canopy coverage and the proportion of residents living in poverty in California urban areas (Figure 8). Additionally, there is a positive relationship between the proportion of neighborhood residents of color and the proportion of impervious land cover and a negative relationship between the proportion of people of color and the amount of tree cover (Figure 9). These data suggest a disproportionate exposure to heat-island risk factors on communities of color and low income.

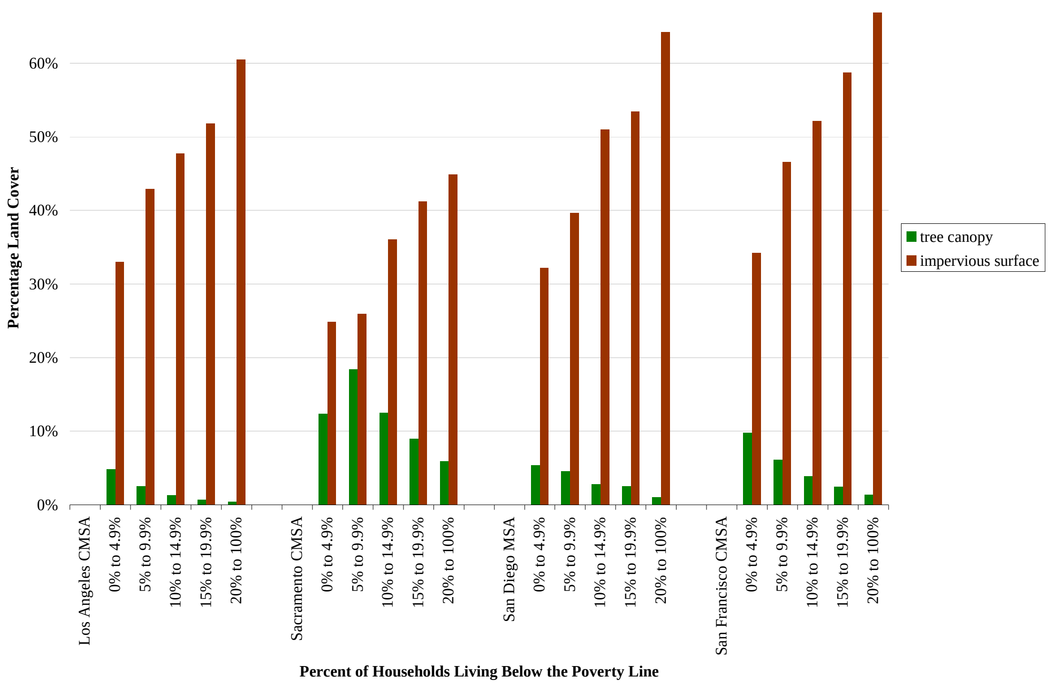


Figure 8. Land Cover Characteristics Across Comparable Neighborhood Poverty Groups in California Urban Areas

Source: Shonkoff et al. (2009)

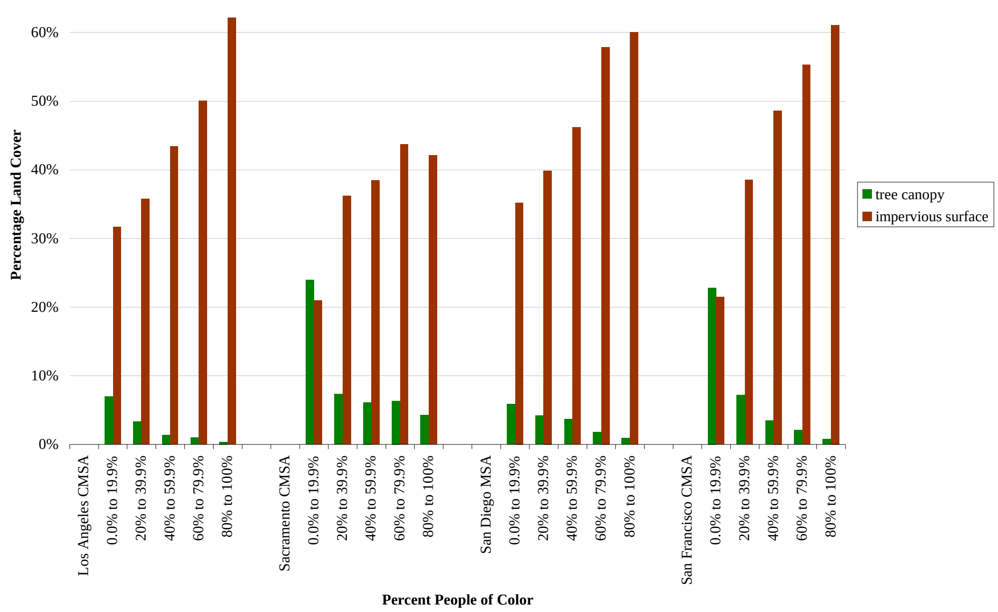


Figure 9. Land Cover Characteristics Across Comparable Neighborhood Racial/Ethnic Minority Groups in California Urban Areas

Source: Shonkoff et al. (2009)

In terms of technological adaptation as an extrinsic factor in heat-associated health outcomes, studies have documented that lack of access to air conditioning is correlated with risks of heat-related morbidity and mortality among urban elderly of low SES in the United States (Kovats and Hajat 2008). In the Los Angeles-Long Beach Metropolitan Area, for example, a higher proportion of African Americans do not have access to air conditioning compared to the general population (59 percent versus 40 percent, respectively). Similar trends hold for Latinos (55 percent) and communities living below the poverty line (52 percent) (UCSB 2004) (Table 2). Although these data do not fully explain the drivers of observed racial and SES disparities in air conditioner ownership, the differential proportions of ownership of these technologies is important because households without air conditioning will have increased exposures during extreme heat events and poor air quality days, when communities are instructed to stay indoors and avoid outdoor pollution exposures and air conditioning can decrease penetration of outside air pollution into one's home (Shonkoff et al. 2009).

In a study using heat-wave data from Chicago, Detroit, Minneapolis, and Pittsburgh, O'Neill et al. (2005) found that African Americans had a 5.3 percent higher prevalence of heat-related mortality than Whites and 64 percent of this disparity is potentially attributable to disparities in prevalence of central air conditioner (AC) technologies (O'Neill et al. 2005). These results are bolstered by other studies that found associations between being African American and a lack of AC as an indicator for vulnerability to heat-related poor health outcomes (Curriero et al. 2002; Greenberg et al. 1983; O'Neill et al. 2003; Rogot et al. 1992; Semenza et al. 1996; Whitman et al. 1997). Although these data are likely generalizable to the California context, future research is needed to assess the impacts of heat events on African-American populations in California.

Table 2. Proportion of Households without Access to Any Air Conditioning by Race and SES, for the Los Angeles-Long Beach Metropolitan Area, California (2003)*

	Total Number of Households ***(General Los Angeles Population)***	**Total Occupied Units** ***(General Los Angeles Population)***	**Black** ***(Not Hispanic)***	**Hispanic**	**Elderly** ***(65 years or older)***	**Below Poverty Level**
All Occupied units	3,131,000	39.7%	58.5%	54.6%	37.5%	51.5%
Renters	1,608,900	48.1%	59.1%	58.4%	38.7%	56.3%
Homeowners	1,522,100	30.9%	57.4%	48.9%	36.8%	38.8%

* Percentages are likely an underestimate of the true value due to the fact that more than one category may apply to a single unit in the dataset.

Adapted from: American Housing Survey for the Los Angeles-Long Beach Metropolitan Area 2004 (USCB 2004)

Further, nearly 84 percent of residents in the Los Angeles metropolitan area rely on cars to commute to work, compared to 7 percent of residents who rely on public transportation (ACS 2007). The paucity of public transit options makes residents extremely reliant on car ownership to meet basic transportation needs.[1] In extreme heat events, households without air conditioning may need to relocate to cooling centers, which can be a logistical challenge for those without access to a car or adequate public transportation. In the Los Angeles-Long Beach Metropolitan Area, compared to White households (7.9 percent), elevated proportions of African-American (20 percent), Latino (17.1 percent), and Asian (9.8 percent) households do not have access to a car (UCSB 2004), thus restricting their capacity to move to cooler areas and government-sponsored cooling stations during extreme heat events.

Material and socioeconomic deprivation, especially in the inner city, is highly correlated with heat-wave and heat-stroke mortality risk in the United States, including California (Klinenberg 2002; Kovats and Hajat 2008; English et al. 2007). For example, the heat wave in Phoenix, Arizona, in 2005 was responsible for thirteen heat-stroke-related deaths, eleven of which were homeless people who tend to lack access to protective material and social resources (Devries 2005).

The intrinsic-extrinsic framework thus highlights some important factors that need to be taken into account for public health vulnerability mapping.

Synthesis Commentary on Frameworks

The above frameworks had some notable overlaps, namely acknowledging that adverse health outcomes from environmental exposures such as heat waves and higher temperatures were caused not only by elevated exposure, but also by greater vulnerability due to intrinsic and extrinsic factors, and less adaptive capacity. There was also recognition in at least two of the frameworks on how cumulative exposures can be assessed in relation to social susceptibilities.

In addition to this review of scholarly and peer-reviewed literature, we also examined government documents, policies and related non-peer review grey literature on climate change adaptation and health in California. Please see Appendix A for this review.

Section 2: Empirical Studies in the San Francisco Bay and Fresno Regions

Based on the Geography of Risk framework from Figure 3 and the literature summarized from above, racial-ethnic minority groups and groups with lower socioeconomic positions may face more climate change impacts and environmental hazard *exposures*. These groups are also more *susceptible* to these exposures due to age, poor nutrition, psycho-social stress, existing disease,

---

[1] Since the 1930s when National City Lines, a holding company run by corporate partners in the automotive industry, bought and dismantled a considerable portion of the public transit infrastructure in Los Angeles, residents without a personal automobile in the Los Angeles-Long Beach Metropolitan Area have been at a severe disadvantage (Kunzli et al. 2003).

poverty, and other material and technological deprivation. Furthermore, these groups have *less adaptive capacity* to deal with adverse impacts because they often lack the social resources to cope.

For our empirical studies, we developed a conceptual framework (Figure 10) for mapping climate change exposures, susceptibilities to those exposures, and adaptive capacity related to human health that is informed by the Geographies of Risk framework. We extend this framework to an operational approach that relies on staged applications of indicators and screening tools. First, we identified, modeled, and mapped those environmental, social, and health factors in the Geography of Risk figure that are closely related to climate change and vulnerability. Second, we quantified the cumulative impacts of four high-priority factors such as heat stress, air pollution, social vulnerability, and adaptive capacity using single and cumulative environmental inequality indices. Third, we applied environmental justice screening tools (Sadd et al. 2011) to map the above four high-priority factors to identify areas within our two study areas with increased vulnerability to the health impacts of climate change.

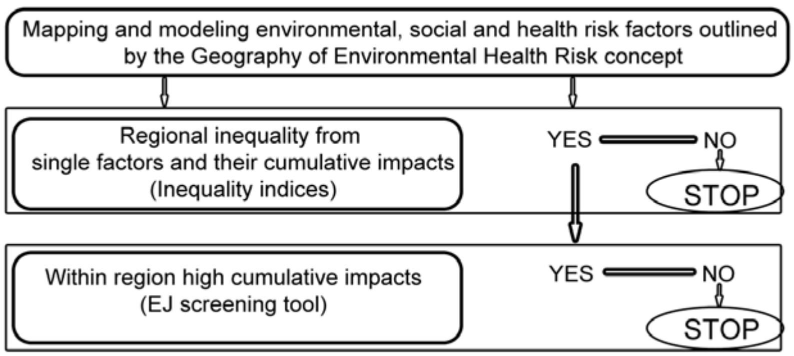


Figure 10. Analysis Framework in Exposure Inequalities of Climate Change

Modeling and Mapping Environmental, Social, and Health Factors Related to Climate Change and Vulnerability: Step I

Based on the literature review, we identified environmental, social, and health factors that are most relevant to climate change and vulnerability. These factors were then used to construct four sets of cumulative inequality indices including (1) heat stress using absolute and relative temperature exceedances; (2) air pollution using NO_2, $PM_{2.5}$, and diesel PM concentrations; (3) social vulnerability using preterm birth and low birth weight, elderly over 65 living alone, and lack of car ownership; and (4) adaptive capacities, including less impervious surface, high tree canopy coverage, and high air conditioning ownership. The following sections describe mapping and modeling some important factors using data sources provided in Table 3. All the modeling results were then projected to the census tract level for both the San Francisco Bay Area and the Fresno region for application in the following steps. We emphasize that there are many other possible factors to consider that are associated with other climate change-related impacts, such as sea level rise flooding risk and infectious disease distribution, but for the purpose of demonstrating our approach, we chose to focus on heat stress and air pollution exposures.

Table 3. Data Sources Used to Estimate Environmental, Social, and Health Risks Related to Climate Change and Vulnerability

Data	Year(s)	Original Data Level	Source
Air Conditioning Usage	2000	ZIP Code/Tract	CEC RASS
Air Pollution Monitoring	1999–2005	At monitoring locations	U.S. EPA
Birth Outcomes	2000–2006	Census Tract	CDPH
Elderly Living Alone	2000	Census Tract	ACS
Household Car Access	2000	Census Tract	ACS
Weather data for heat stress	2001–2005	At monitoring locations	CIMIS
Impervious Surface	2001	30 meter raster	NLCD
Tree Canopy	2001	30 meter raster	NLCD
Race-ethnicity and Socioeconomic Status	2000	Census Tract	U.S. Census

CEC RASS = California Energy Commission Residential Appliance Saturation Survey, U.S. EPA = United States Environmental Protection Agency, CDPH = California Department of Public Health, ACS = American Community Survey, CIMIS = California Irrigation Management Information System, NLCD = National Land Cover Database

Modeling Air Conditioning Usage Prevalence

Data on the prevalence of central air conditioning ownership (excluding swamp coolers and window cooling units) were obtained from the California Energy Commission (Energy Commission), based on the 2009 Residential Appliance Saturation Survey (http://www.climatechange.ca.gov/), reported at the ZIP code level. Because the data were acquired from a survey, proportion of households using air conditioning in a ZIP code based on the survey did not represent the true proportion of population in that ZIP code who actually had air conditioning. Quite a few communities did not have survey data on air conditioning usage. Air conditioning data were therefore estimated for all 2009 ZIP codes for the state using a spatial empirical Bayes model by Drs. Paul English and Eric Roberts, from the California Department of Public Health. This model assumes a beta distribution for air conditioning prevalence and uses the (weighted) counts of respondents, with and without air conditioning in each ZIP code, as inputs.

For each ZIP code *i*, the prior distribution is calculated using all of the respondents in ZIP codes adjacent to *i*, and the posterior distribution is the prior distribution updated by the counts in ZIP code *i* itself. We estimated posterior means, and posterior 2.5th and 97.5th-percentiles for ZIP codes in the San Francisco Bay Area and Fresno. Note that some ZIP codes did not have any respondents for the RASS (indicated by "NA" in the file), and thus air conditioning prevalence was not estimated. The estimated means were then calculated for year 2000 Census tracts using an area-weighted average of the ZIP codes within a given census tract for the San Francisco Bay Area and the Fresno region to derive tract-level estimates for air conditioning prevalence (see Figure 11a and b).

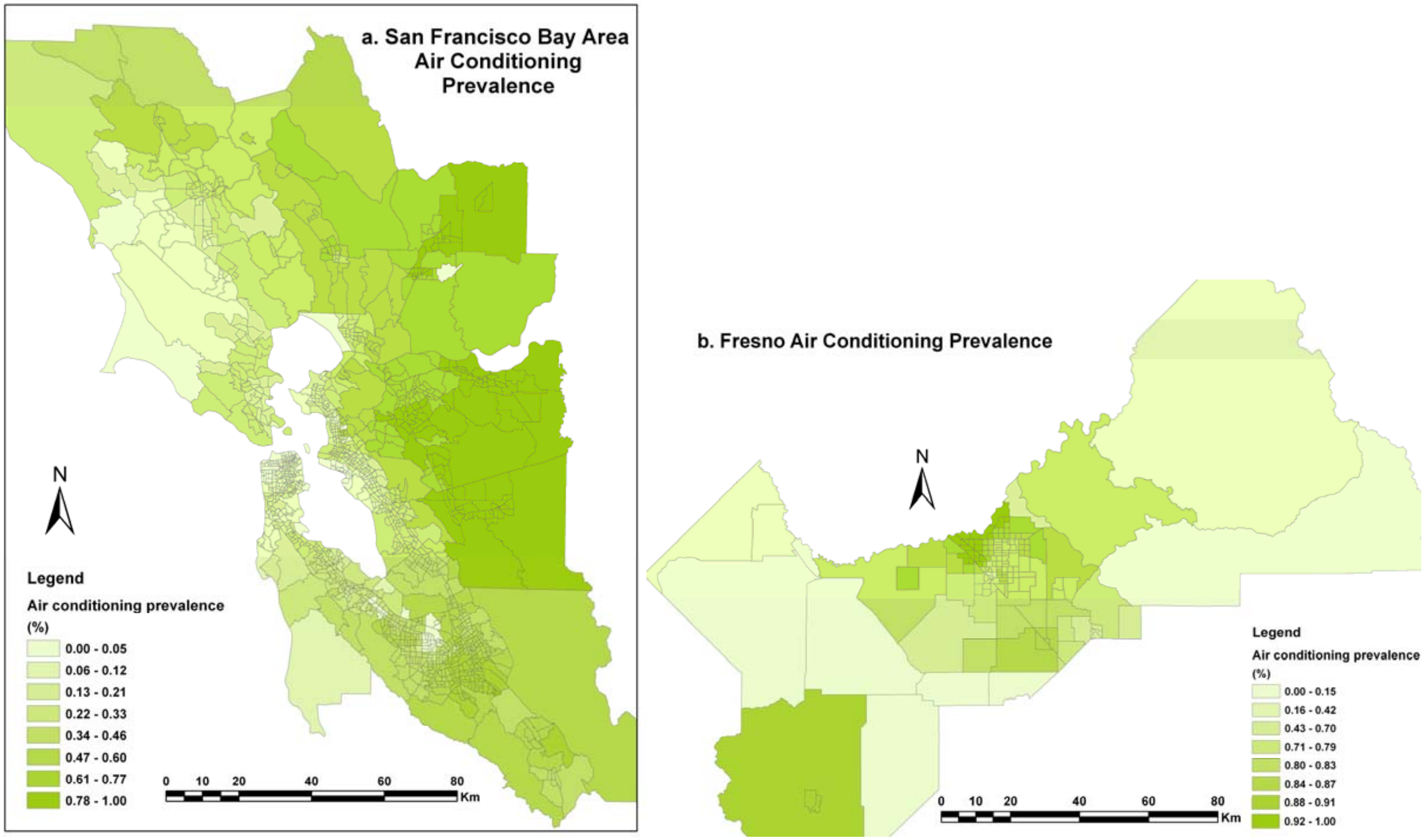


Figure 1. Modeled San Francisco Bay Area (a) and Fresno Region (b) Air Conditioning Usage Prevalence from the 2009 Residential Appliance Saturation Survey

Modeling Air Pollution

The air pollution measurements included in this analysis are NO_2, $PM_{2.5}$, and diesel particulate matter (PM). Because of differences in sources of emission and chemical reactions, the spatial distribution and gradients of these pollutants are not the same. Because of these differences, we modeled each individual pollutant in a way that best characterizes its spatial distribution.

For NO_2, we used A Distance Decay Regression Selection Strategy (ADDRESS) (Su et al. 2009) to model spatial variation in traffic pollutants. This method is a form of land use regression (LUR) that selects spatial covariates at the spatial distance where they have the highest correlation with NO_2. At the first step, the series of distance decay curves is constructed using the measured concentrations against the chosen spatial covariates. A variable with the highest correlation to pollutant levels at its optimized buffer distance is chosen as the first predictor of the LUR model from all the distance decay curves. Starting from the second step, the prediction residuals are used to construct a new series of distance decay curves, and the variable of the highest correlation at its optimized buffer distance is chosen to be added to the model. This process continues until a variable being added does not contribute significantly ($p < 0.10$) to the model performance. The distance decay curve yields a visualization of change and trend of correlation between the spatial covariates and air pollution concentrations or their prediction residuals, providing a transparent and efficient means of selecting optimized buffer distances. Empirical comparisons suggest that the ADDRESS method produced better results than a manual stepwise selection process of limited buffer distances. The method also enables researchers to understand the likely scale of variables that influence pollution levels, which has potentially important ramifications for planning and epidemiological studies (Figures 12a and 12b).

For $PM_{2.5}$, land use regression modeling techniques were used. As the distribution of $PM_{2.5}$ was left skewed, a natural logarithm transformation was applied. A Deletion Substitution Algorithm was used to select the best model for $PM_{2.5}$ prediction, and the detailed methodology could be found from the Jerrett et al. California Air Resources Board project report (Jerrett 2011). The final land use regression prediction was then projected to census tract for multi-year average $PM_{2.5}$ concentrations (Figure 13a and b).

Diesel PM data were acquired from the U.S. Environmental Protection Agency for 2005 (U.S. EPA 2011) (Figure 14a and b). Census tract level ambient diesel PM concentrations were modeled using the Assessment System for Population Exposure Nationwide (ASPEN). ASPEN consists of a dispersion and a mapping module. The dispersion module is a Gaussian formulation for estimating ambient annual average concentrations at a set of fixed receptors within the vicinity of the emission source. The ASPEN model takes into account important determinants of pollutant concentrations, including the rates of emission releases, the location of these releases, the height from which the pollutants are released, the wind speeds and directions from the meteorological stations nearest to the release, the breakdown of the pollutants in the atmosphere after being released (i.e., reactive decay), the deposition or settling of pollutants out of the atmosphere, and the atmospheric transformation of one pollutant into another (i.e., secondary formation). The mapping module produces a concentration at each census tract. ASPEN treats each source as a "pseudo-point" source located at the centroid of the census tract where it is located (the source's resident tract). ASPEN estimates ambient concentrations for a pre-set receptor grid, and then interpolates ambient concentrations from the grid receptors to each census tract centroid outside of the source's resident tract (the source's non-resident tract). To estimate the average concentration for a resident tract, ASPEN represents the area source for a tract as multiple pseudo-point sources geographically dispersed throughout the tract, rather than as a single source. Ambient concentrations in the resident census tract are estimated with spatial averaging of the ambient concentrations at all grid receptors that fall within the bounds of the tract. When these resident tract and non-resident-tract concentrations are calculated for all sources, the concentrations from all sources are summed for each tract.

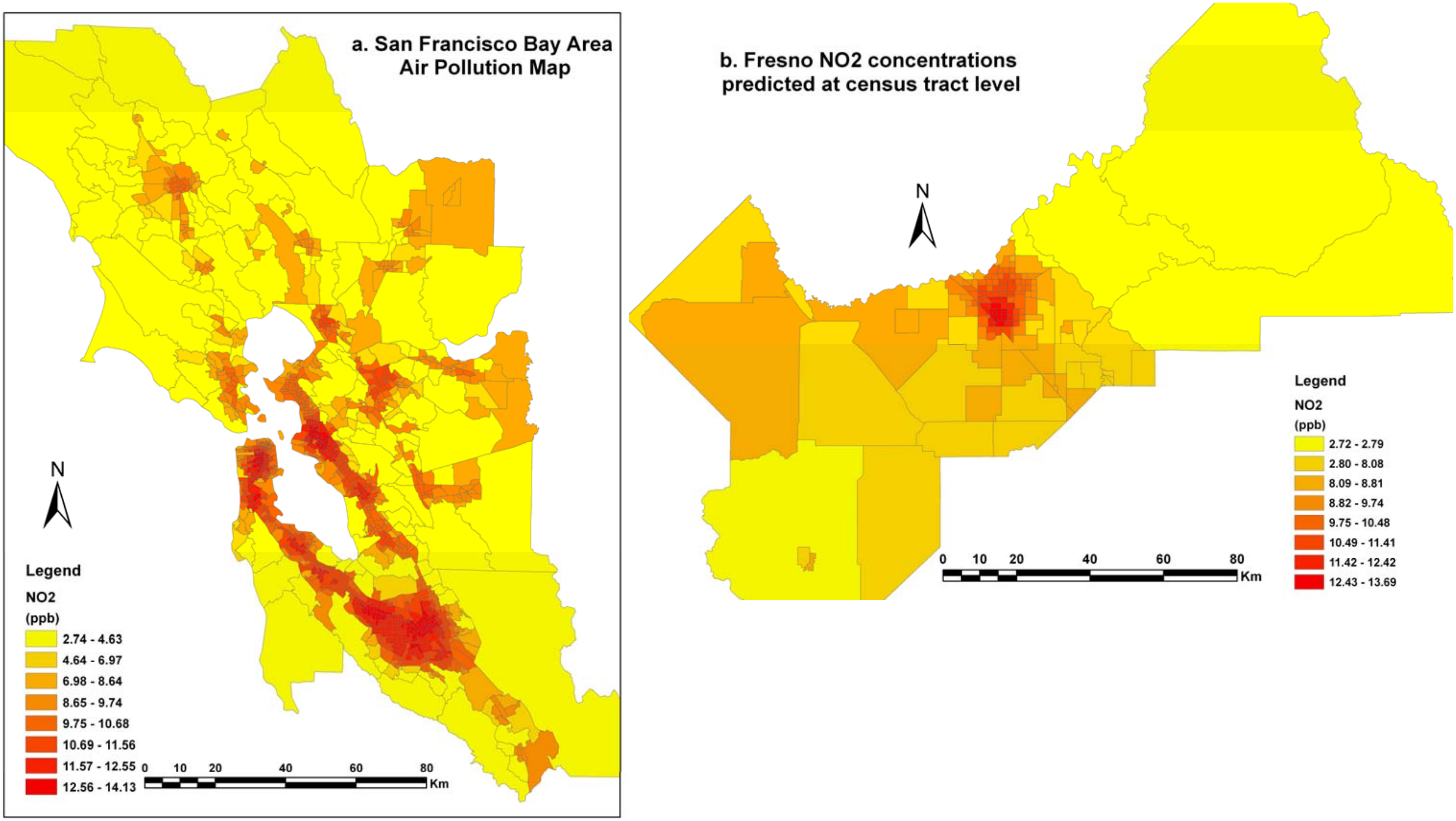


Figure 22. Modeled NO_2 Concentrations Predicted at the Census Tract Level for (a) San Francisco Bay Area and (b) the Fresno Region County

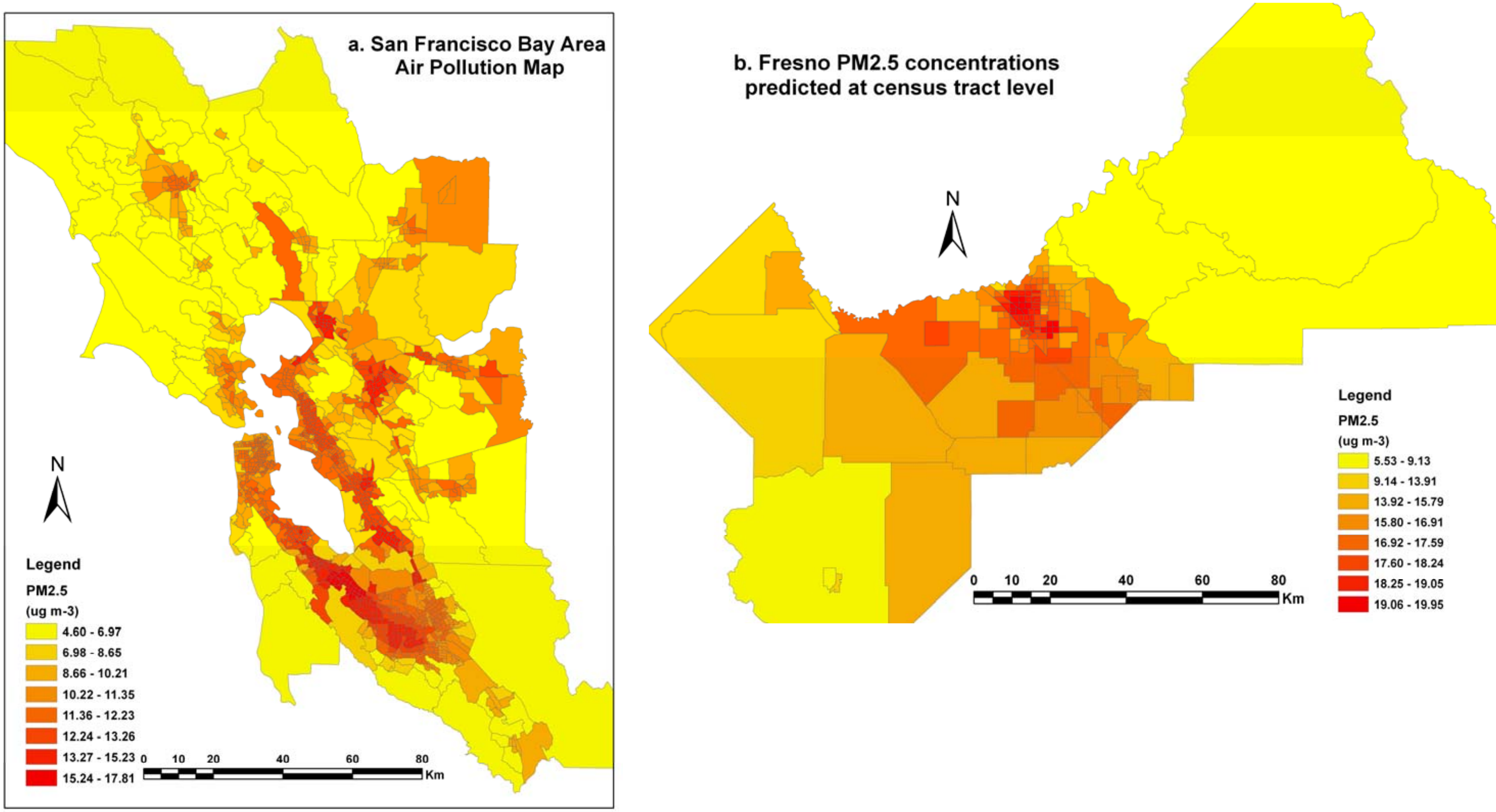


Figure 33. Modeled $PM_{2.5}$ Concentrations Predicted at the Census Tract Level for (a) San Francisco Bay Area and (b) Fresno County

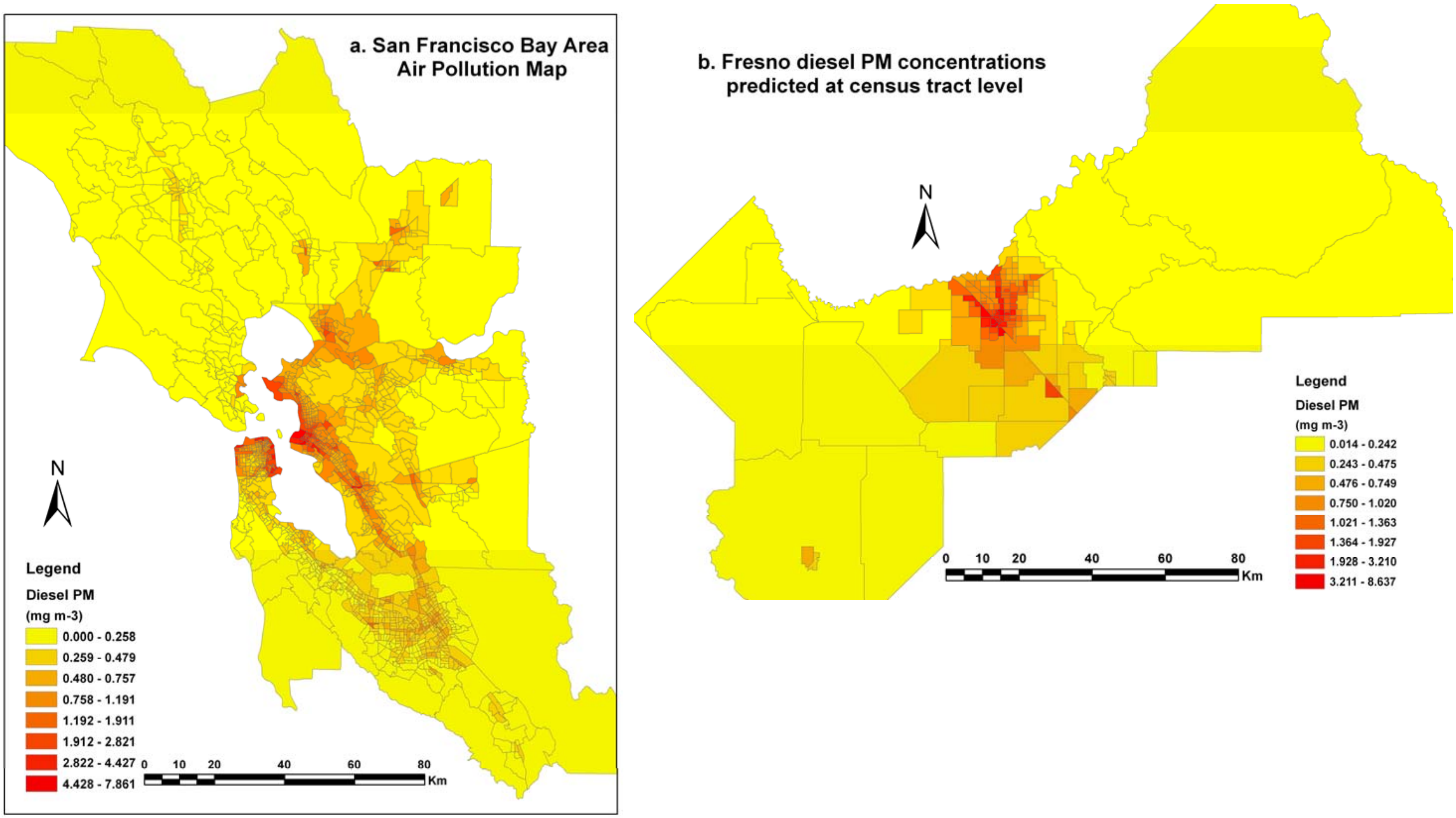


Figure 44. Modeled Diesel PM Concentrations Predicted at the Census Tract Level for (a) San Francisco Bay Area and (b) Fresno County

Adverse Birth Outcomes

Low birth weight is associated with increased risk of death in the first year of life and throughout childhood (McCormick 1985), and there is even evidence that adverse birth outcomes can affect health outcomes, including hypertension, heart disease, and noninsulin-dependent diabetes later in life (Osmond and Barker 2000). Therefore, prevalence of adverse birth outcomes at the neighborhood level can be a predictor of health vulnerabilities of a community. Data on birth outcomes was obtained from California's Center for Health Statistics at the California Department of Health Services. From these data, the percent of live births that were preterm (defined as those infants born at fewer than 37 weeks of gestation) and/or were low birth weight (defined as infants born weighing less than 2500 grams) was calculated for each census tract (Figure 15a and b).

Elderly Living Alone and Household Car Access

The proportion of elderly residents living alone in a tract (aged 65 and older, living alone in an owned or rented housing unit, divided by the tract population) (Figure 16a and b) and the proportion of households with no vehicle (owned or rented households with no available vehicle (Figure 17a and b), divided by the total number of owned and rented housing units) were derived from the American Community Survey, five-year estimates, 2005–2009 (USCB 2010).

Modeling Summer Heat Stress Using Weather Monitoring Data

Increases in temperature and radiation directly raise body temperature, and increased humidity slows cooling of the body by decreasing sweat evaporation (English et al. 2009). An increase in wind speed, by contrast, speeds up sensible and latent heat loss (Dikmen and Hansen 2009). Therefore, high temperature, high humidity, and low wind speed increase an individual's risk of heat illness (Maloney 1998). For summer heat stress, Steadman's (1984) apparent temperature was used and calculated by:

$$T_{ap} = -1.8 + 1.07 * T_{amb} + 2.4 * P - 0.92 * v + 0.042 * Q \quad (1)$$

where T_{ap} is the estimated apparent temperature and T_{amb} the measured ambient temperature, both in °C; P is vapor pressure (kPA), v is wind speed (m/s), and Q is solar radiation (W/m^2). In estimating daily heat stress, the daily maximum ambient temperature was used for T_{amb}, and daily average vapor pressure and wind speed for P and v, respectively.

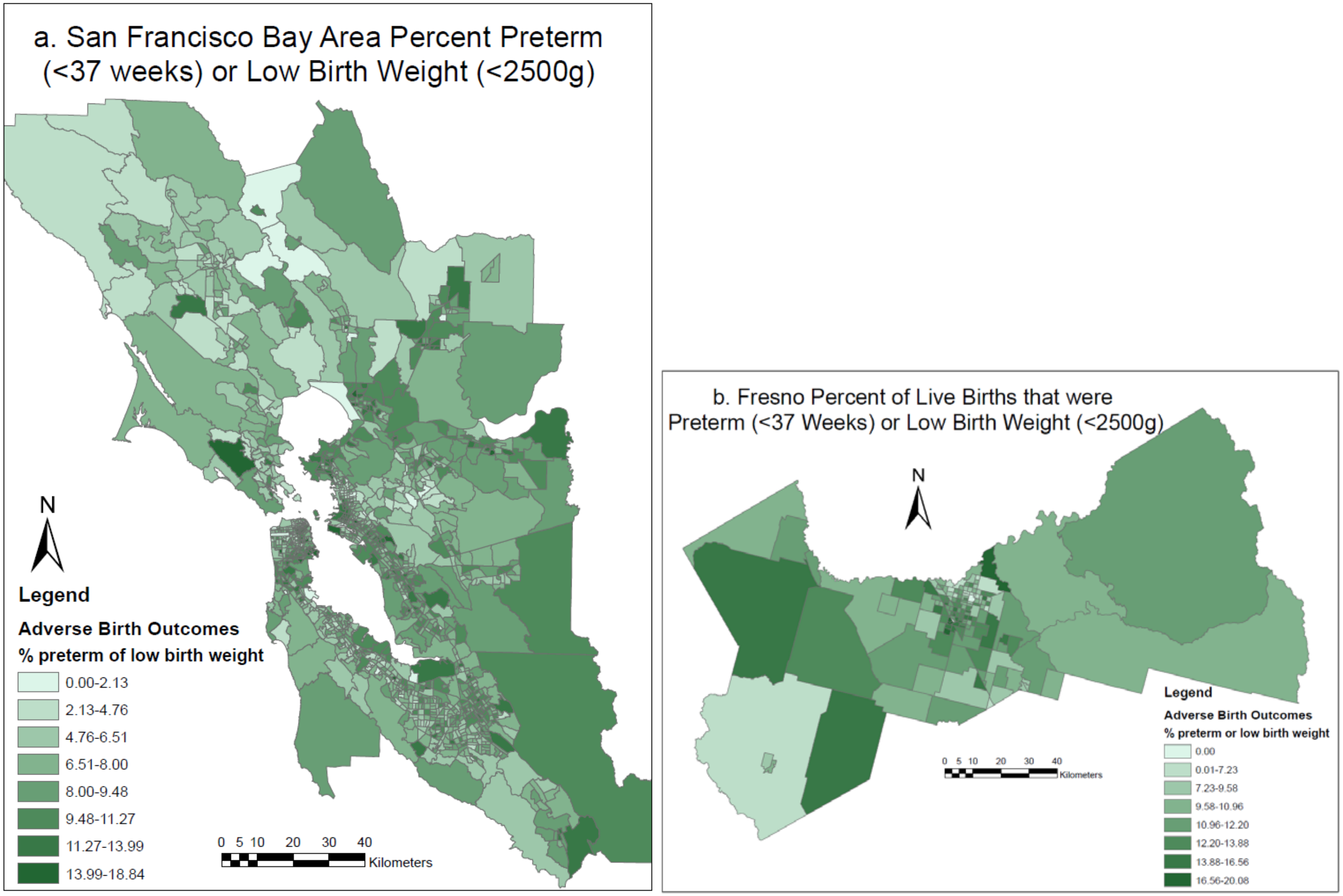


Figure 5. San Francisco Bay Area (a) and Fresno (b) Percent of Live Births That Are Preterm or Low Birth Weight

Source: California Department of Public Health

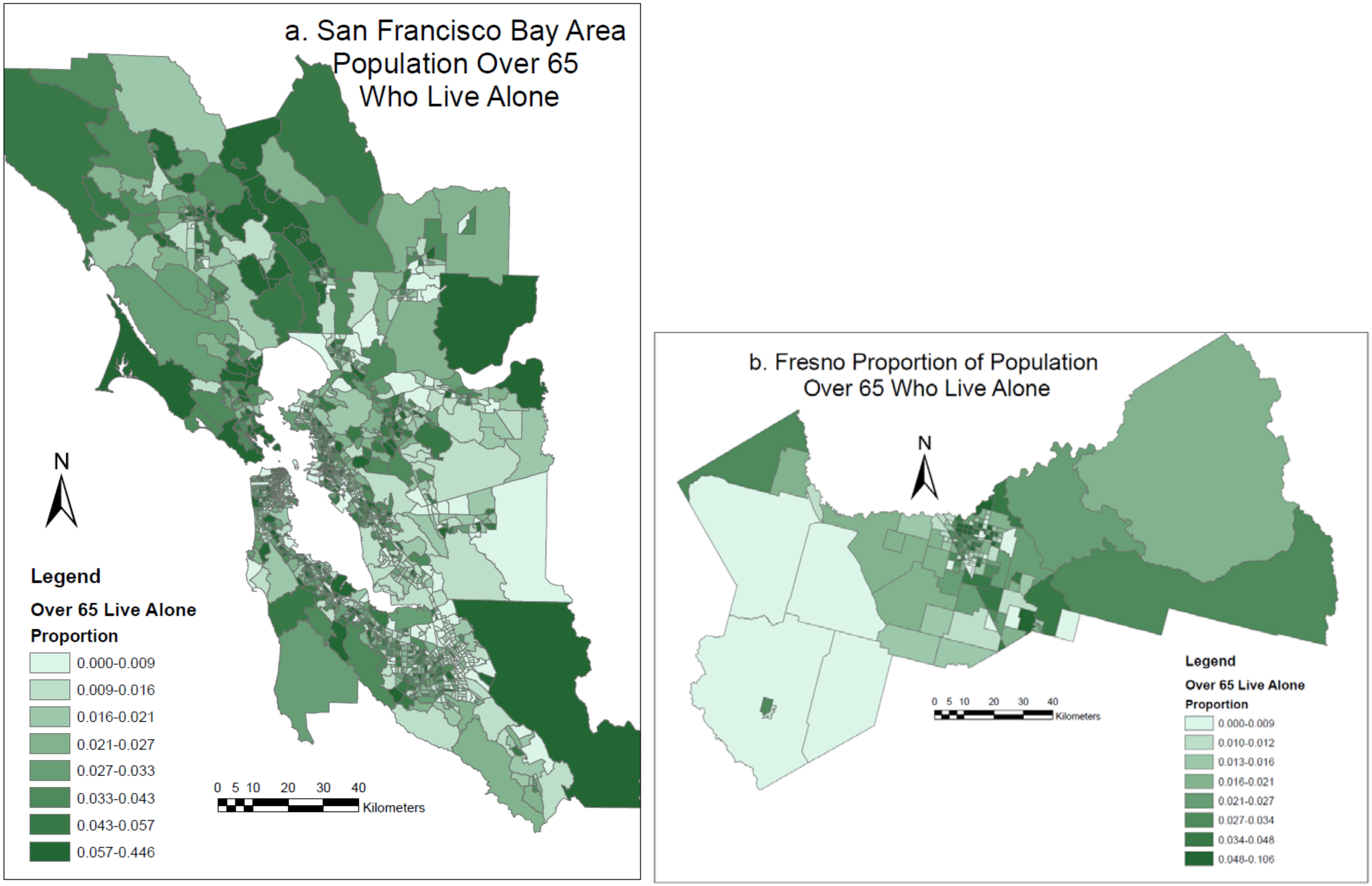


Figure 6. San Francisco Bay Area (a) and Fresno (b) Population Over 65 Who Live Alone

Source: American Community Survey 2005–2009

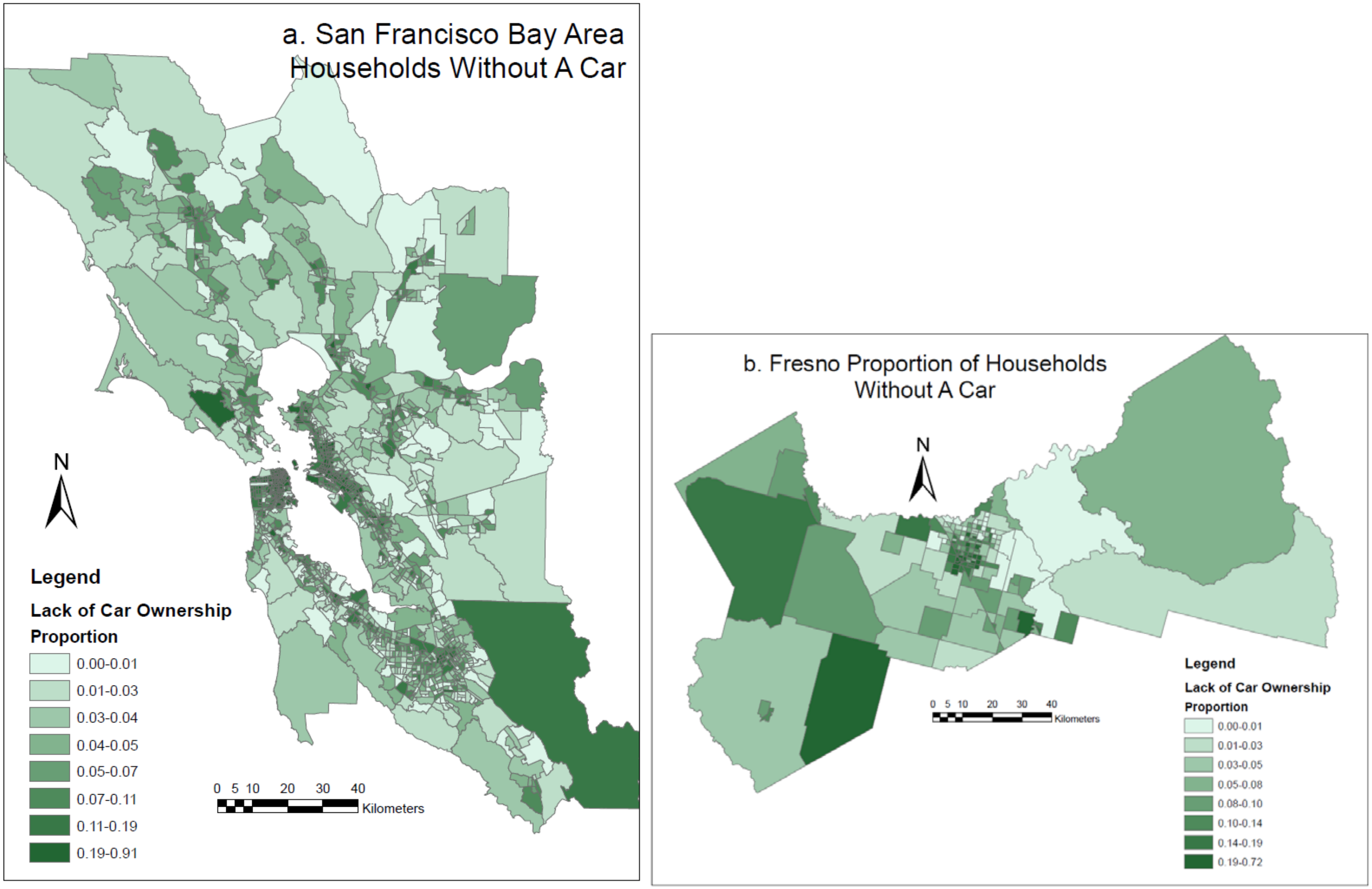


Figure 7. San Francisco Bay Area (a) and Fresno (b) Proportion of Households Without a Car

Source: American Community Survey 2005–2009

Meteorological data were acquired from the California Irrigation Management Information System (CIMIS). Daily data in the summer months (July, August, and September) for 2001–2005 from 123 monitoring stations were used to estimate summer heat stress. Literature suggests that when the temperature is above 40°C (104°F), extreme caution should be taken for people working outside (Harlan et al. 2006). The positive difference between the observed apparent temperature and 40°C for a day was treated as the measure of absolute temperature exceedance. For each monitoring station for the summer period, the sum of the absolute exceedances were taken and then divided by the number of days with temperature measurements above 40°C in the same period, to derive an estimate of the daily absolute temperature exceedance for that summer season. This value was estimated for each of the five years and then further averaged to reflect the five-year mean daily absolute temperature exceedance (°C per day).

Distance to the coast (kilometers, km), latitude (degrees), and elevation (meters, m) data (Brody et al. 2008) were then used to spatially model the per-day absolute temperature exceedance for the State of California using data from the 123 monitoring stations (see details in Table 4). The model explained 74.5 percent of the model variation (R^2) and was then used to spatially predict daily absolute temperature exceedance for each census tract for the San Francisco Bay Area and the Fresno region for the 2001–2005 time period (Figure 18a and 19a).

Table 4. Model of Heat Stress in Daily Absolute Temperature Exceedance for the State of California Using 123 Monitoring Stations for 2001–2005*

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF**
(Constant)	28.778	3.590		8.017	.000		
Latitude	-.732	.099	-.342	-7.369	.000	.989	1.011
Elevation	-.002	.000	-.433	-8.693	.000	.863	1.159
Distance from coast	.055	.003	.872	17.463	.000	.858	1.166

*: Latitude = latitude in degrees; Elevation = elevation in meters; Distance = distance to coast in kilometers.
**: VIF = Variance Inflation Factor.

Individuals' response to heat is also influenced on their local climate. The positive difference between observed daily apparent temperature and the 30-year normal maximum temperature for each monitoring station based on its 1971–2000 historic temperature data for a summer season (July, August, and September) was used to calculate the relative temperature exceedance. These differences were then divided by the number of days with temperature measurements above the historical 30-year normal maximum temperature in the same period to derive a daily relative temperature exceedance (°C per day) for that summer season. The estimations were conducted for the 2001–2005 summer seasons and daily relative temperature exceedance of a five-year mean were used for our analysis. Because of the lack of 30-year meteorological data to derive historical normal maximum temperatures for each monitoring station using the CIMIS meteorological data, the historical normal maximum temperature data from the U.S. National Climate Data Center (NCDC) were used and assigned to each CIMIS monitoring station based on the closest distance principle. The relative daily temperature exceedance for a summer season were calculated as follows:

$$E_j = \frac{1}{n}\sum_{i=1}^{n}(Tap_{ij} - \overline{T}_j^{\max})$$

where $\overline{T}_j^{\max}$ is the 30-year normal maximum temperature from July, August, and September for 1971–2000 measured at the j^{th} location. Tap_{ij} is the i^{th} day's apparent temperature in the three-month summer period that exceeds the 30-year normal maximum temperature at the j^{th} location; n is the total number of days with apparent temperature greater than the mean maximum temperature. An inverse distance weighting function was used to assign the daily relative temperature exceedance from the 123 monitoring stations to the census tracts in the San Francisco Bay Area (Figure 18b) and the Fresno region (Figure 19b). This metric reflects the estimated relative degree of temperature exceedance at a neighborhood scale.

Impervious Surface and Tree Canopy Cover from NLCD

We used the 2001 National Land Cover Dataset (USGS 2007) which reported the estimated proportion of tree canopy and impervious surface with approximately 30-meter resolution. We summarized these data into block groups by averaging the reported tree canopy (Figure 20a and 20b) and impervious surface (Figure 21a and 21b) proportions across the block group areas, and then using population counts from the 2000 census, averaged these block group averages up to population-weighted census tract averages.

Race-ethnicity and Socioeconomic Status from the U.S. Census

Race-ethnicity and socioeconomic data were obtained from the 2000 U.S. Census at the census tract level. *Racial-ethnic composition* was defined as the percentage of nonwhites in the population (Figure 22a and 22b). *Socioeconomic position* was estimated as the proportion of the population with an income less than 200 percent of the federal poverty level (FPL) (Figure 23a and 23b).

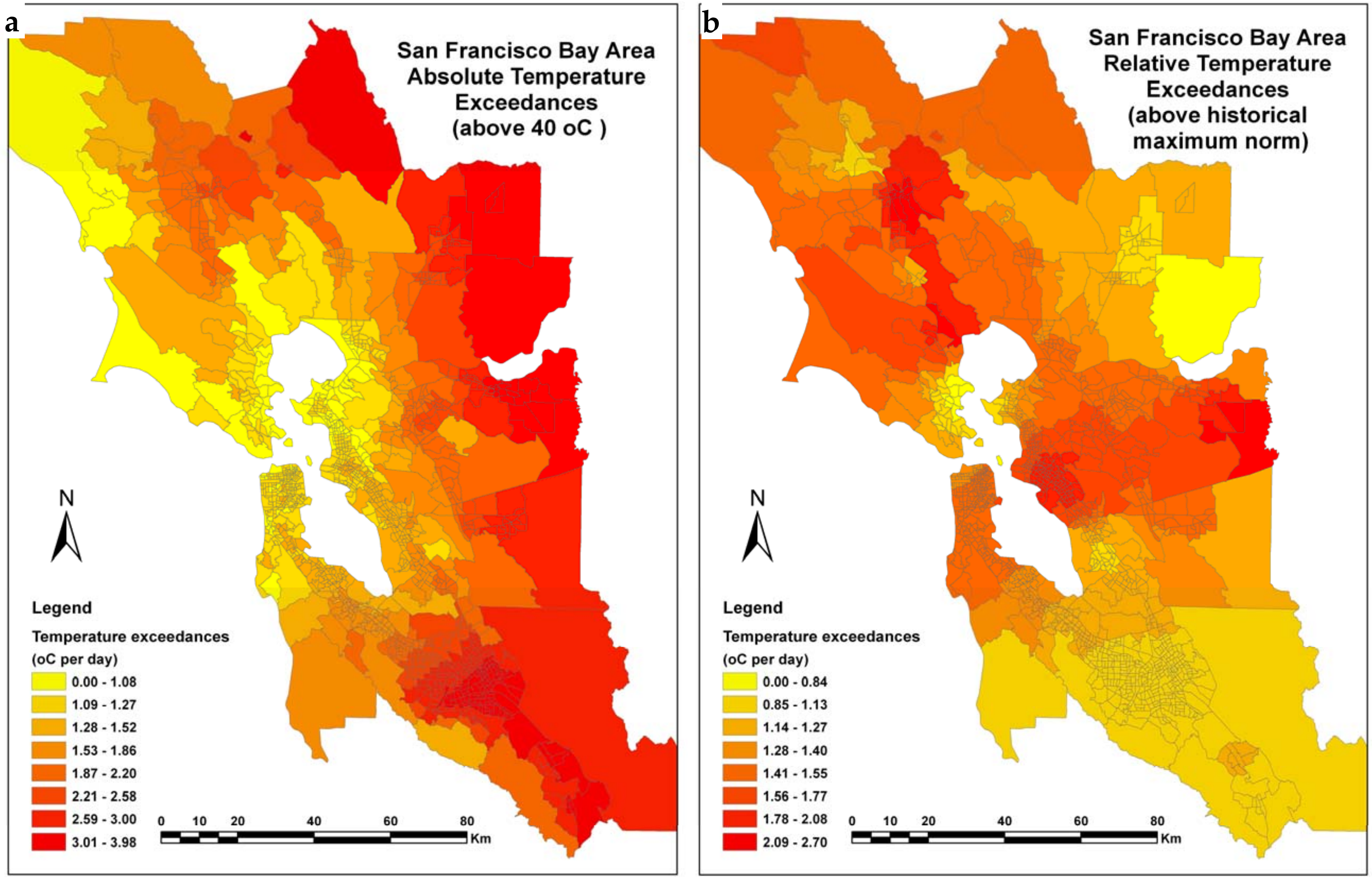


Figure 8. San Francisco Bay Area Heat Stress for Daily (a) Absolute and (b) Relative Temperature Exceedance (°C per day)

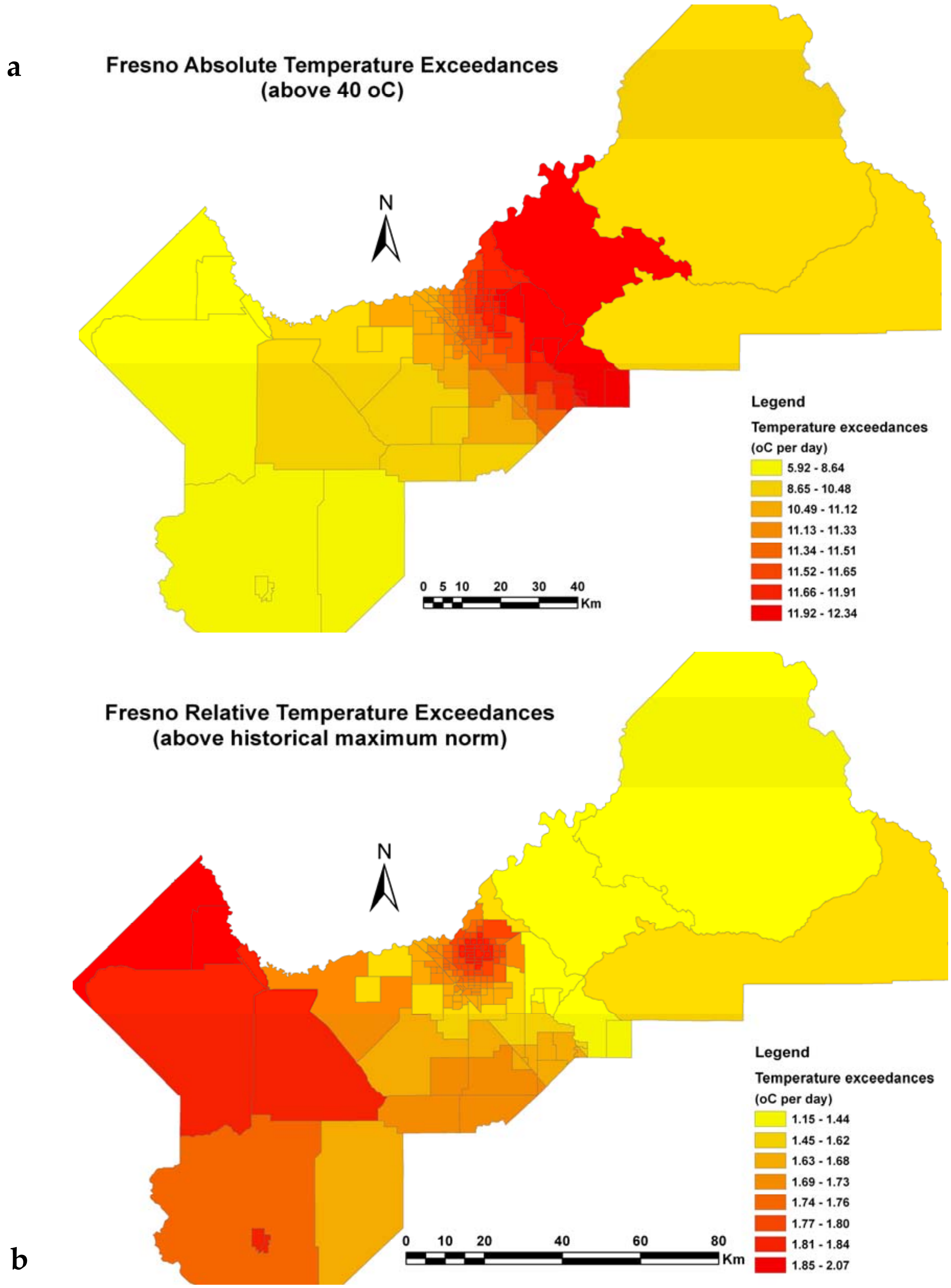


Figure 9. Fresno Region Heat Stress Indices for Daily (a) Absolute and (b) Relative Temperature Exceedance (°C per day)

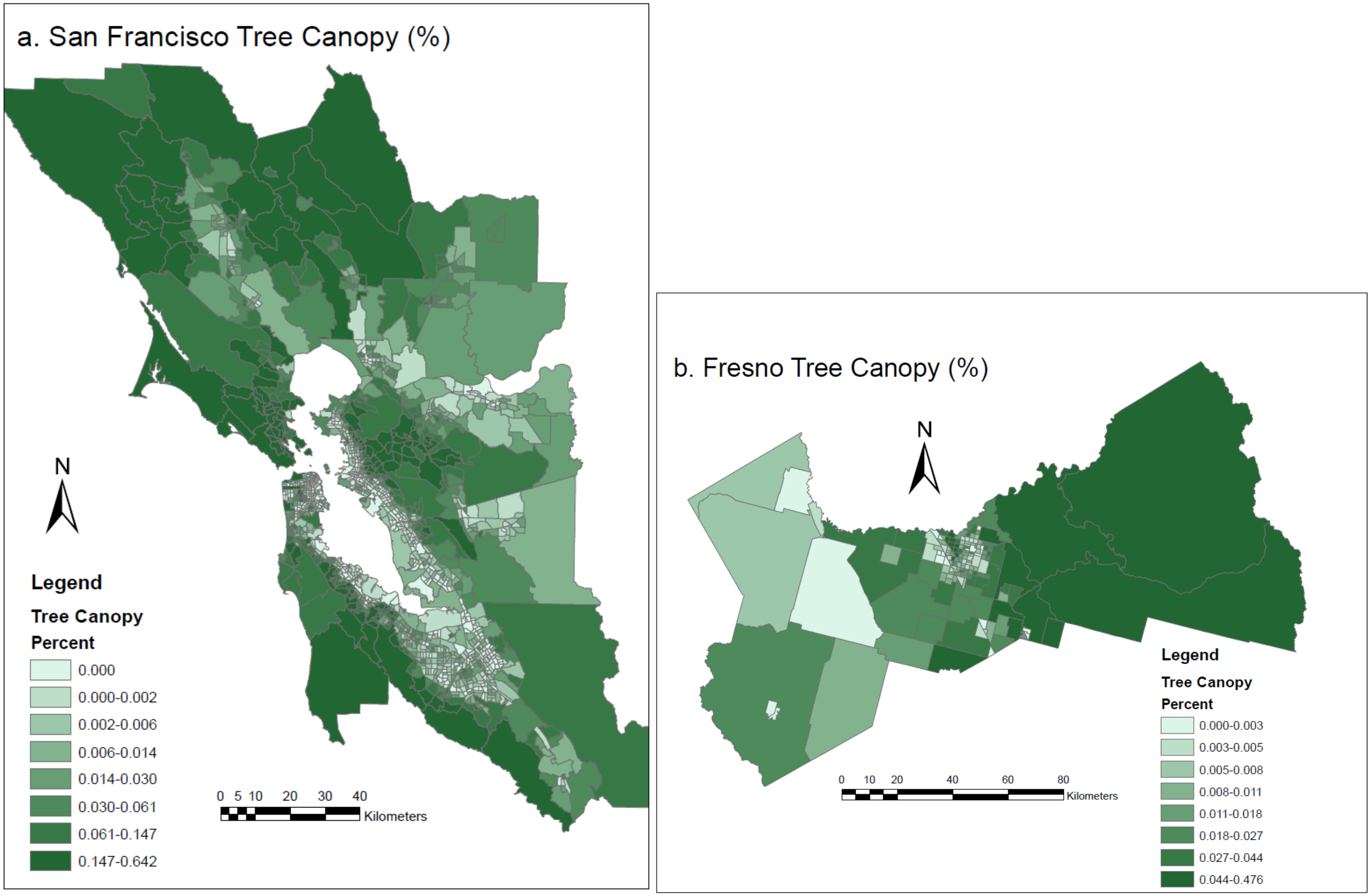


Figure 20. San Francisco Bay Area (a) and Fresno (b) Tree Canopy Cover from the National Land Cover Database 2001

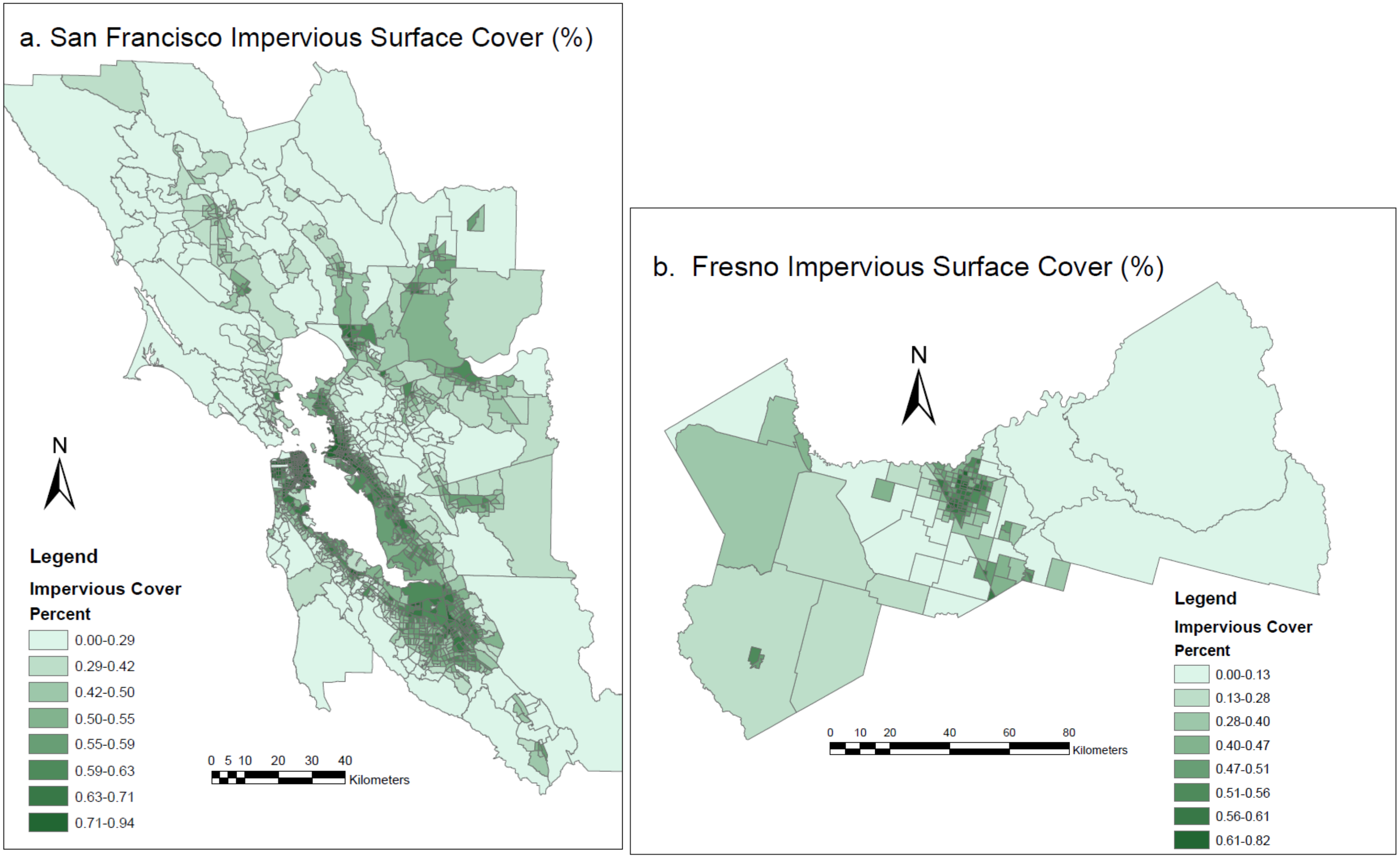


Figure 10. San Francisco Bay Area (a) and Fresno (b) Impervious Surface Cover from the National Land Cover Database 2001

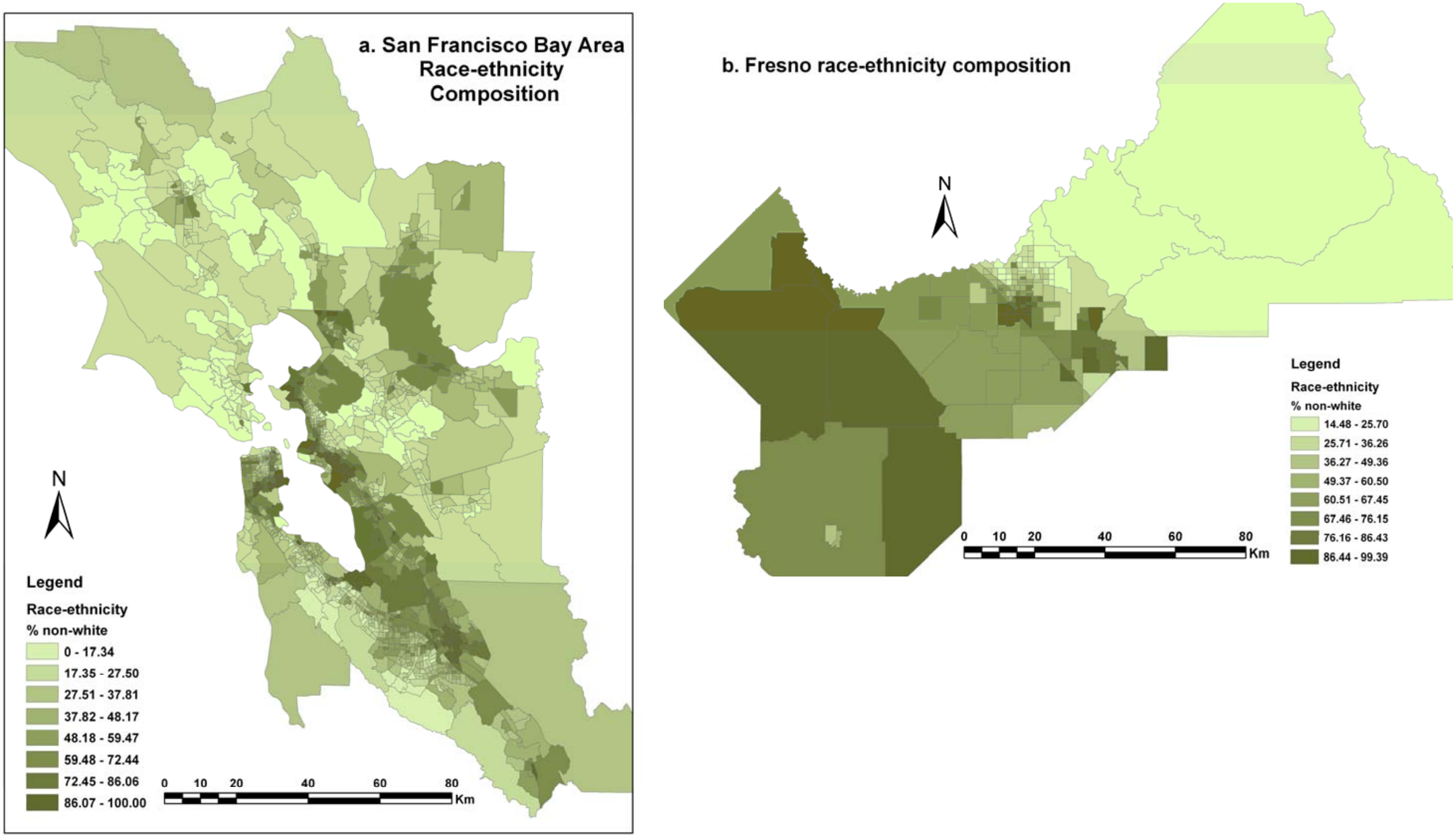
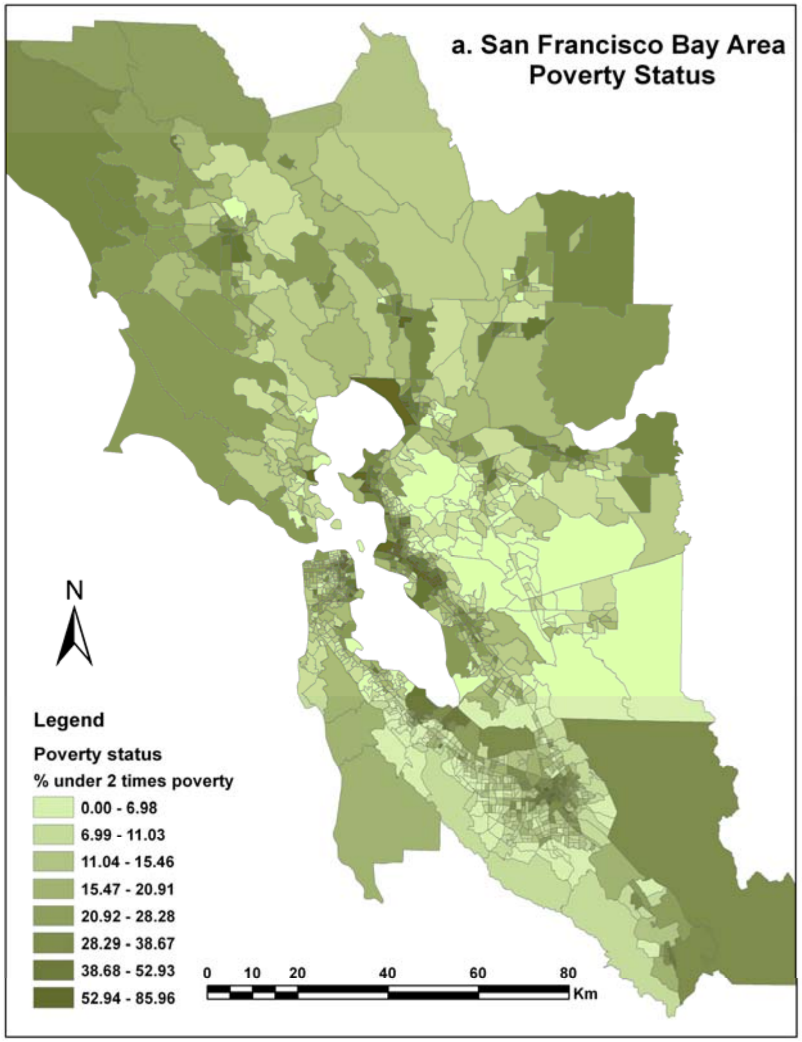


Figure 11. San Francisco Bay Area (a) and Fresno Region (b) Race-ethnicity Composition from the 2000 U.S. Census



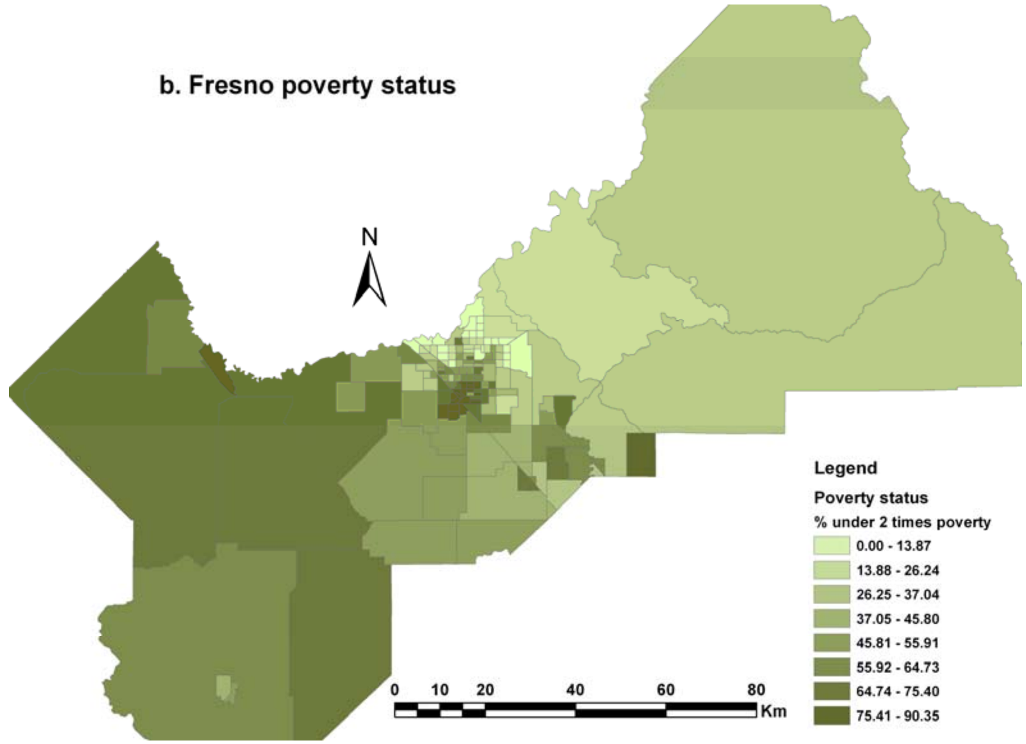


Figure 12. San Francisco Bay Area (a) and Fresno Region (b) Poverty Status from the 2000 U.S. Census

Quantifying Regional Environmental Inequalities with Exposure to Single and Cumulative Environmental Hazards: Step II

Cumulative Inequality Indices

We employed the CEHII methodology outlined in the frameworks section and pioneered by Su et al. 2009. We assumed the existence of multiplicative impacts, and the cumulative impacts are aggregated by a synergistic weighting function (U.S. EPA 2006; Mauderly and Samet 2008). Here we selected two widely used metrics of disparities. The first metric was census tract-level racial-ethnic composition, and was defined as the percentage of nonwhites in the population. The second metric was census tract-level socioeconomic position, estimated as the proportion of the population with an income less than 200 percent of the federal poverty level (FPL).

We estimated four sets of cumulative inequality indices to compare against these two disparity metrics, including heat stress, air pollution, social vulnerability, and adaptive capacities. As stated above, we used estimates of daily relative and absolute temperature exceedance as indicators of heat stress. Based on Figure 24, inequalities from heat stress are relatively small (the maximum cumulative inequality being 0.028); however, they are all significantly different from the equality line ($p < 0.05$). In both the San Francisco Bay Area and the Fresno region, we saw that neighborhoods with greater percentage of nonwhites or greater percentage of population in poverty had relatively lower inequality in exposure to heat stress (positive signs), demonstrating moderate protection effect from heat for those disadvantaged groups.

Inequalities in Heat Stress

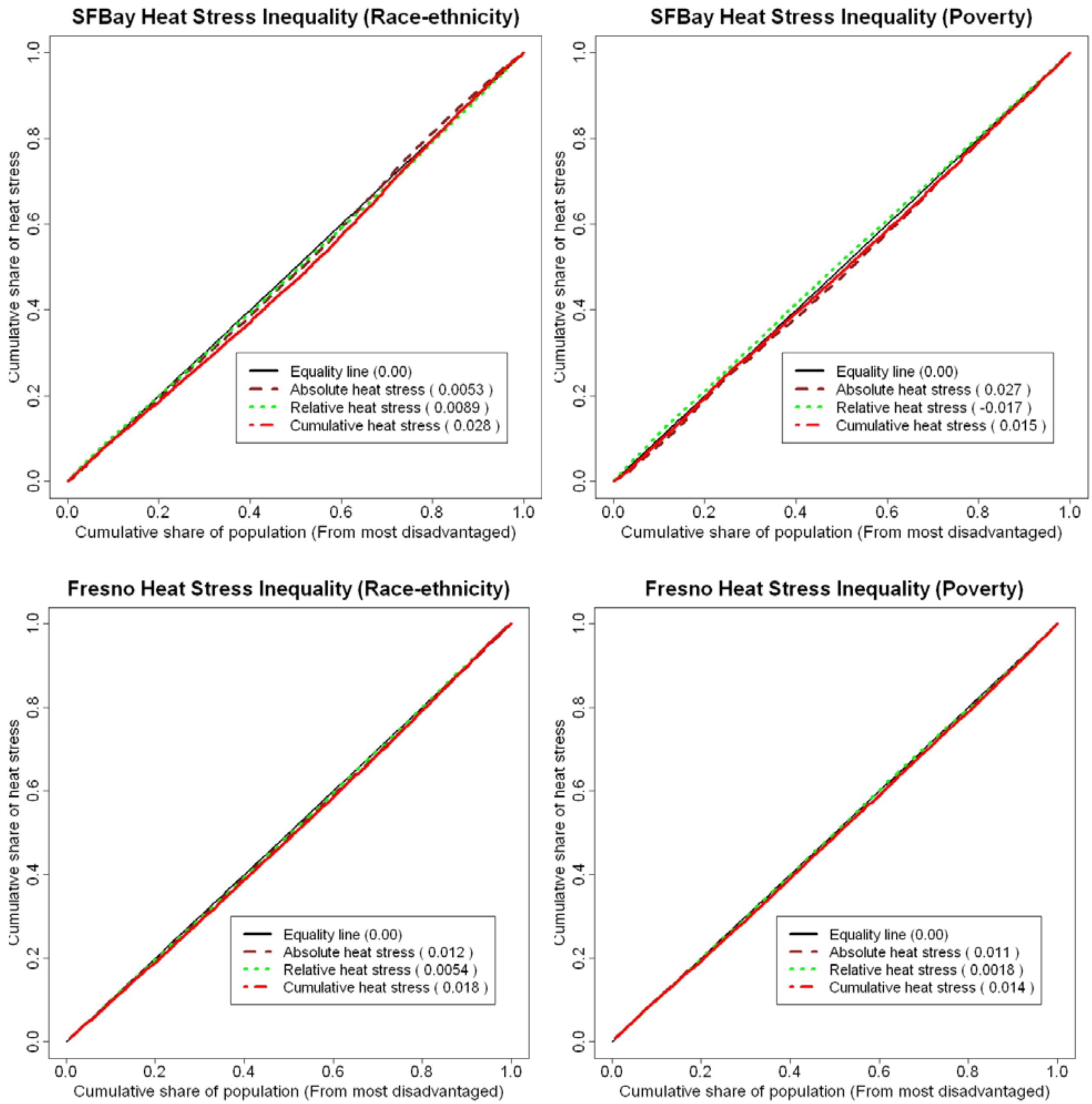


Figure 13. Single and Cumulative Inequalities in Heat Stress for the San Francisco Bay Area (upper) and the Fresno region (lower) Based on Race-ethnicity (left) and Poverty Status (right)

Inequalities in Air Pollution

We used three air pollutants—NO_2, $PM_{2.5}$, and diesel PM—for air pollution exposure inequality analysis. The CEHII indices based on racial-ethnic composition and poverty status are displayed in Figure 25.

Individually, air pollution from $PM_{2.5}$ has the lowest degree of inequality for both race and poverty compositions. By contrast, exposure to diesel PM has the highest degree of inequality. All the single and cumulative indices demonstrate that neighborhoods of higher minority composition or higher poverty status experience greater exposures.

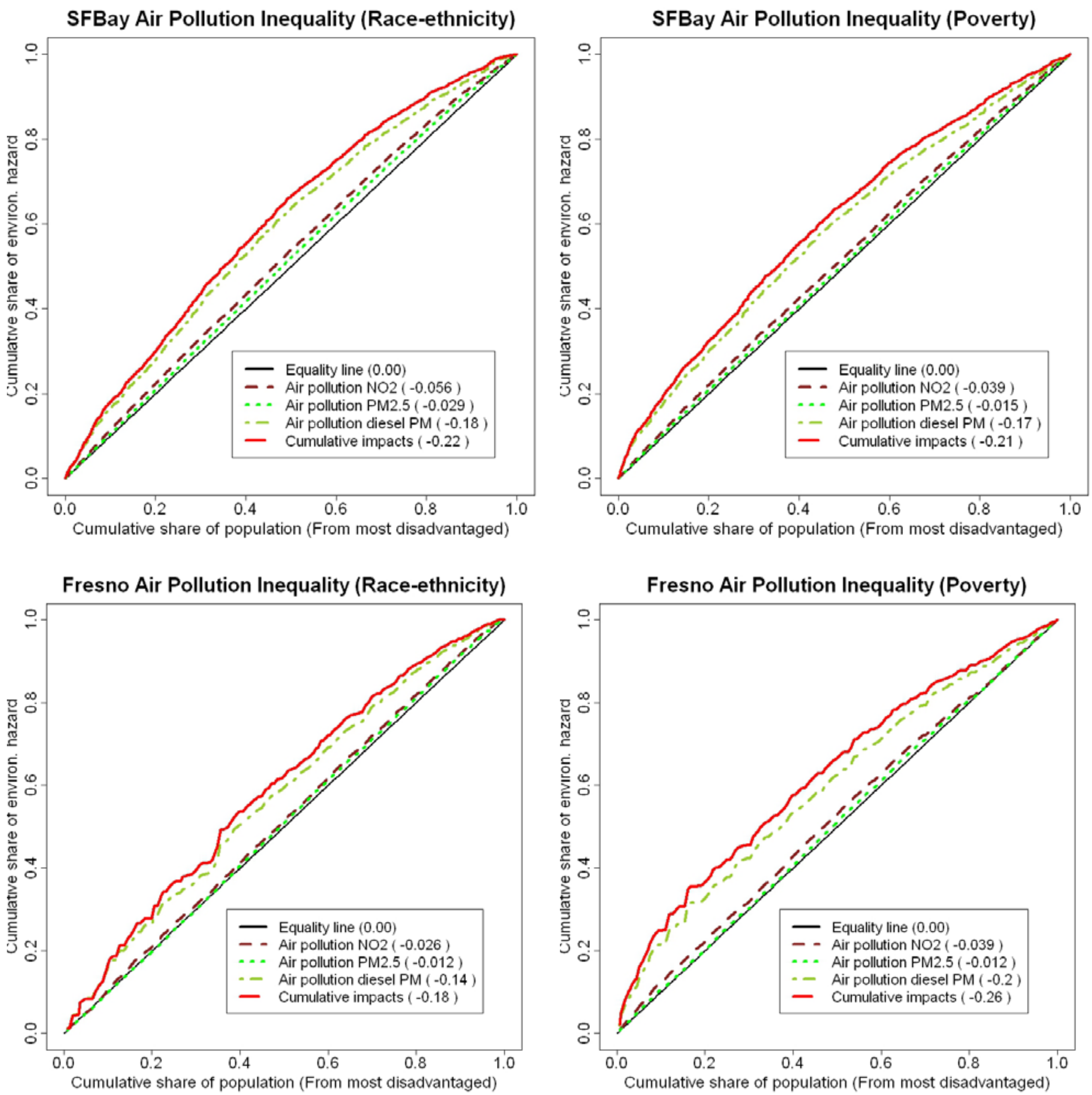


Figure 14. Single and Cumulative Inequalities in Air Pollution for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right)

Inequalities in Social and Health Vulnerability

To investigate inequalities in social and health vulnerability, we used three factors: adverse birth outcome (preterm births and low birth weight), elderly over 65 living alone, and lack of car ownership. Similar to inequalities for air pollution, low-income communities, and communities of color face greater social vulnerability (Figure 26). Car ownership showed the highest degree of inequality. Generally, the degrees of social vulnerability inequality are greater than those of air pollution exposure inequality. Compared to race-ethnicity composition, poverty status showed greater inequality, especially for car ownership.

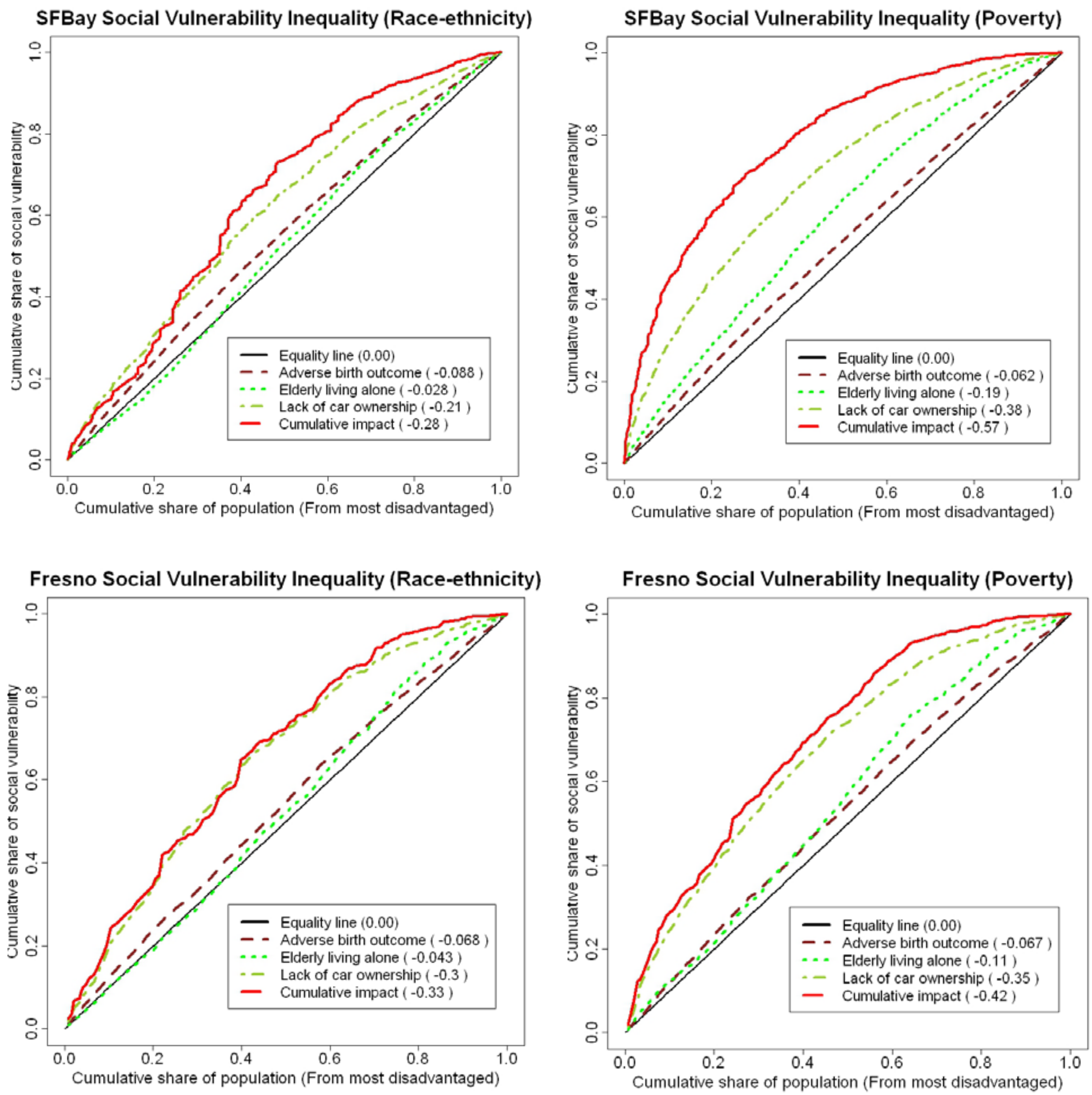


Figure 15. Single and Cumulative Inequalities in Social Vulnerability for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right)

Inequalities in Climate Change Adaptive Capacity

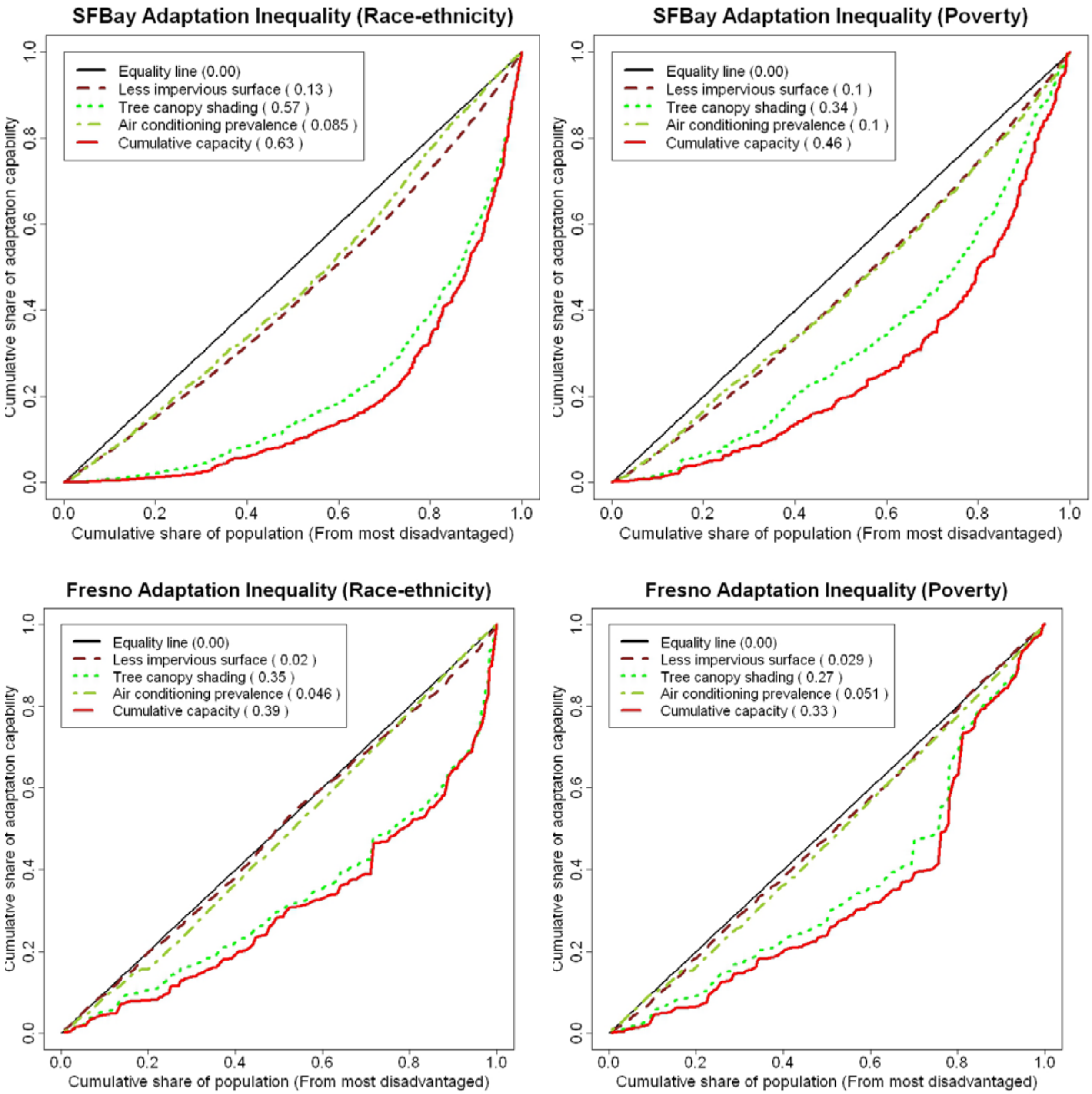


Figure 16. Single and Cumulative Inequalities in Climate Change Adaptation for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right)

For climate change adaptive capacity, we investigated inequalities in impervious surface, tree canopy, and air conditioning prevalence (Figure 27). Communities with more people living in poverty have less vegetation cover (i.e., opposite of impervious surface) and tree canopy protection effects. These disadvantaged groups are also less likely to have air conditioning. Among the three factors considered, tree canopy shading had the highest degree of inequality.

Overall, the cumulative inequalities for adaptive capacity are greater in the San Francisco Bay Area than in the Fresno region for climate change adaptation capabilities.

Cumulative Inequalities of the Four Impacts

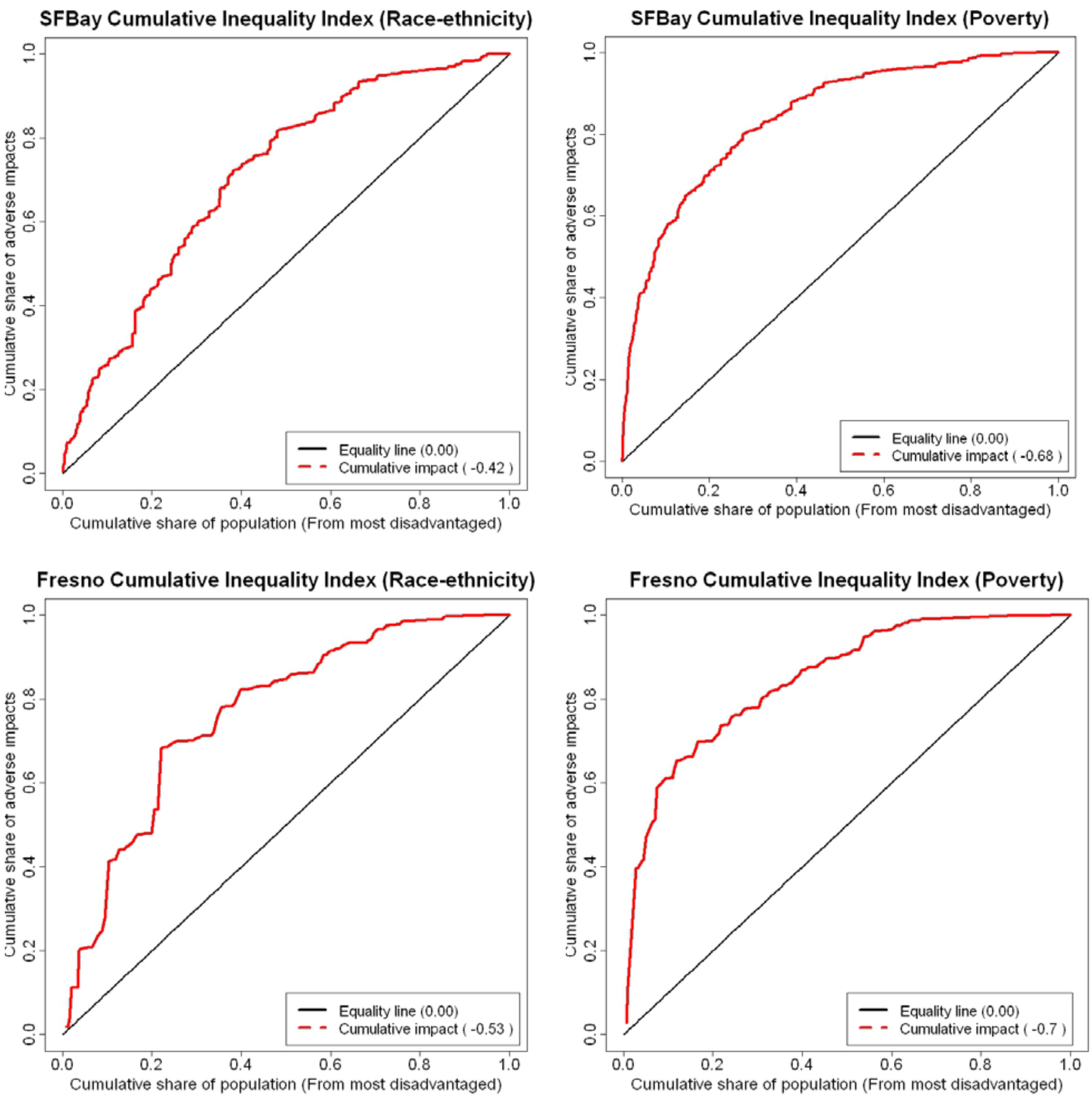


Figure 17. Cumulative Inequalities in Considering all the Four Aspects of Impacts for the San Francisco Bay Area (upper) and the Fresno Region (lower) Based on Race-ethnicity (left) and Poverty Status (right)

We also investigated the cumulative inequalities from the four aspects of impacts, including heat stress, air pollution, social vulnerability, and adaptive capacity. The results show inequalities for the low-income communities and communities of color in the San Francisco Bay Area and the Fresno region: the degree of inequality is generally greater than 0.50 (Figure 28). For race-ethnicity, the communities of color had cumulative impacts 50 percent more than those of whites; for poverty, the low-income communities had cumulative impacts 70 percent more than those of more affluent counterparts.

Identifying Within-Region Environmental Inequalities with Exposure to Cumulative Environmental Hazards: Step III

We used the Environmental Justice Screening Method (EJSM) tool outlined by Sadd et al. (2011) to examine the relative rank of cumulative impacts and social vulnerability within metropolitan regions and to determine environmental justice areas based on more than simply the demographics of income and race. The EJSM tool maps cumulative impacts onto cumulative impact (CI) polygons—for this analysis, we used census tracts. In the Sadd et al. (2011) study, a set of 23 health, environmental, and social indicators of impacts were organized into three categories: (1) hazard proximity and land use, (2) air pollution exposure and health risk, and (3) social and health vulnerabilities.

Based on data availability, and to be comparable with the categories used in the regional CEHII quantitative assessment of cumulative environmental hazards in these regions, we used indicators as described in Steps I and II. These indicators included heat stress rather than hazard proximity and added climate change adaptive capacity. In summary, our indicators included (1) heat stress composed of relative and absolute heat stress, (2) air pollution composed of NO_2, $PM_{2.5}$, and diesel PM, (3) social and health vulnerability composed of adverse birth outcomes, elderly living alone, and lack of car ownership and (4) climate adaptive capacity composed of tree canopy shading, impervious cover, and air conditioning prevalence.

To calculate the vulnerability indicator scores, each vulnerability indicator was normalized, and then the quintiles of this distribution were assigned scores ranging from 1 to 5, with 1 being the lowest vulnerability and 5 the highest. To make one category of vulnerability comparable with another, the total vulnerability of each category was calculated as the summed score of the component indicators divided by the number of indicators considered in that category. The cumulative vulnerability from the four categories for a census tract was then calculated as the summed score of the four category means.

EJ Screening Results

The maps below show the results of this EJSM with cumulative impacts from heat stress, air pollution, social and health vulnerability, and climate adaptive capacity for both the San Francisco Bay Area and the Fresno regions.

San Francisco Bay Area

Figures 29a–e display the EJSM maps for the San Francisco Bay Area. A higher score indicates greater vulnerability. For example, a census tract with a higher score in heat stress demonstrates greater heat stress vulnerability for that census tract. For climate change adaptive capacity, a higher score shows greater inability for adaptation.

For the San Francisco Bay Area, the maps demonstrate that different parts of the region have higher vulnerability for different components of vulnerability. The areas with highest heat stress are in the northern and eastern areas (Figure 29a), which correspond to areas with higher temperatures as the result of being farther from the ocean and bay, which have cooling winds. The most vulnerable areas for air pollution exposures are on the most heavily trafficked highway corridors surrounding the most populated areas of the San Francisco Bay Area, such as 880 in the East Bay and 101 along the Peninsula connecting San Jose and San Francisco (Figure 29b). The social and health vulnerabilities and the lack of adaptive capacities both demonstrate that the most vulnerable areas as the most populated urban areas (Figures 29c and 29d). For adaptive capacity, as expected, lack of tree canopy is in urban areas. In the areas where there is less of a likelihood of having air conditioning it is because the climate is much cooler. Also, in the urban areas of the San Francisco Bay Area, there may be lower car ownership because of the costs of purchasing and maintaining a car, especially for parking than for other areas, which could explain the greater vulnerability for social and health vulnerabilities in the urban areas. The cumulative map demonstrates higher overall vulnerability in the urban areas of the San Francisco Bay Area (Figure 29e).

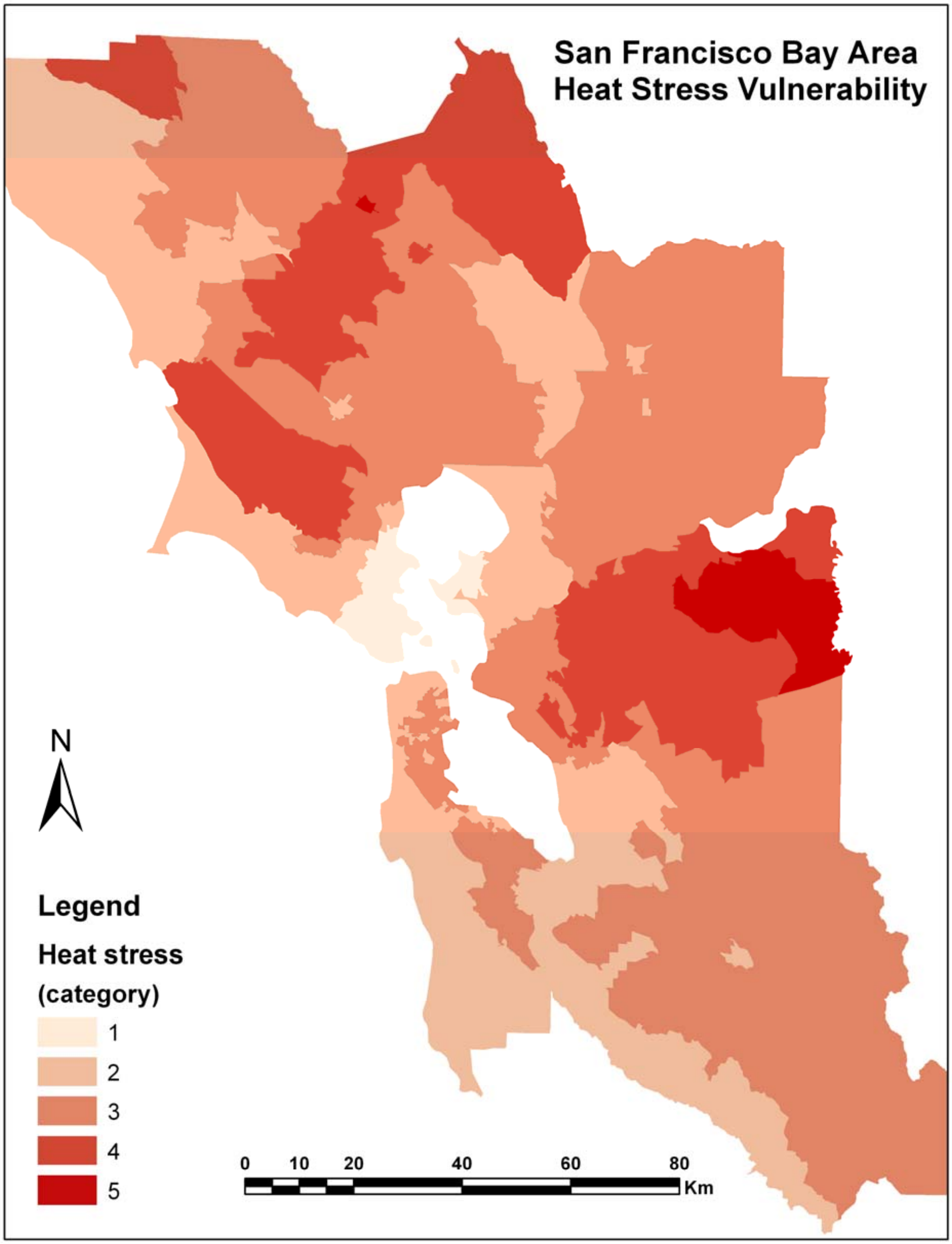


Figure 18a. Quintile Heat Stress Vulnerability Scores at the Census Tract Level in the San Francisco Bay Area

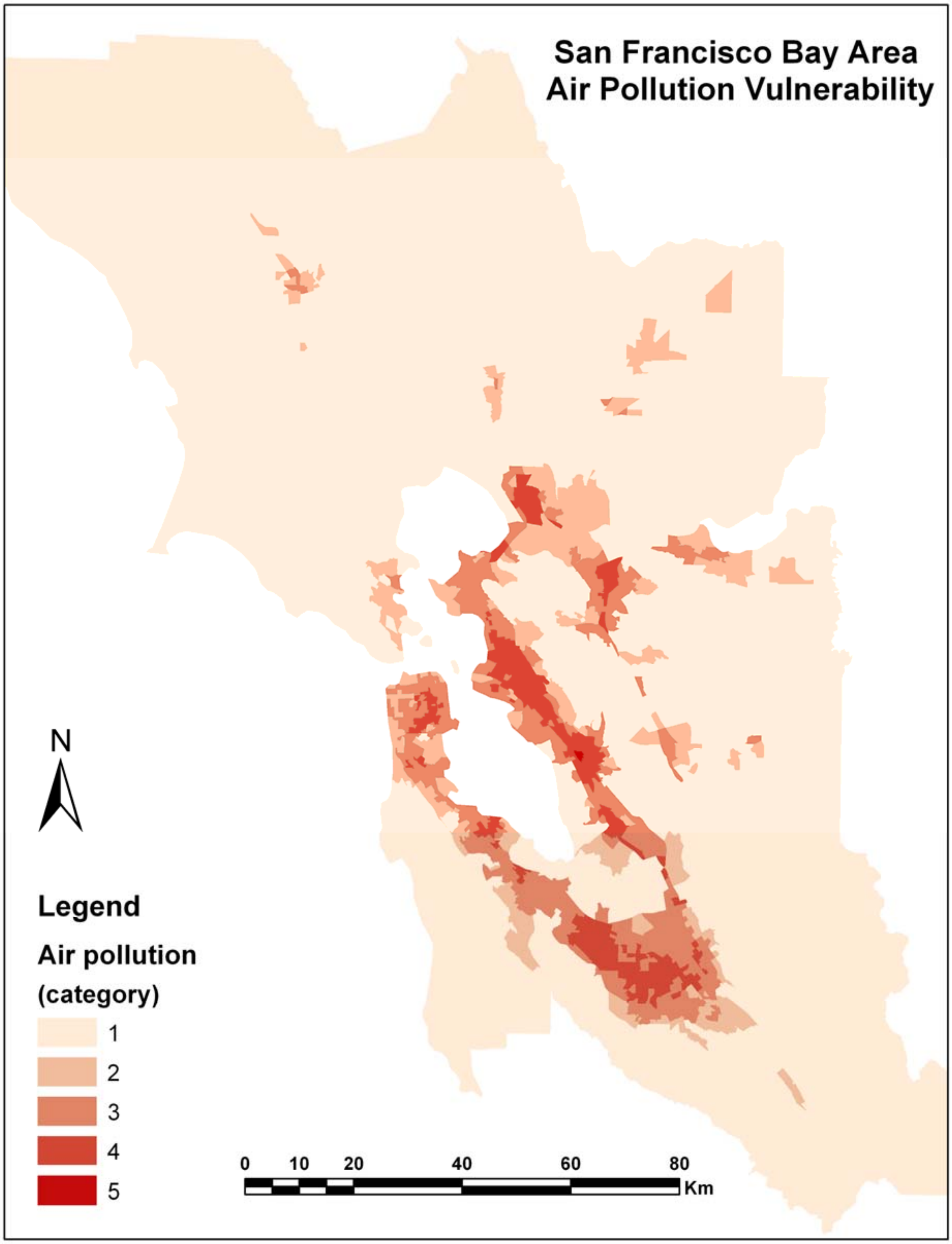


Figure 29b. Air Pollution Quintile Scores at the Census Tract Level in the San Francisco Bay Area

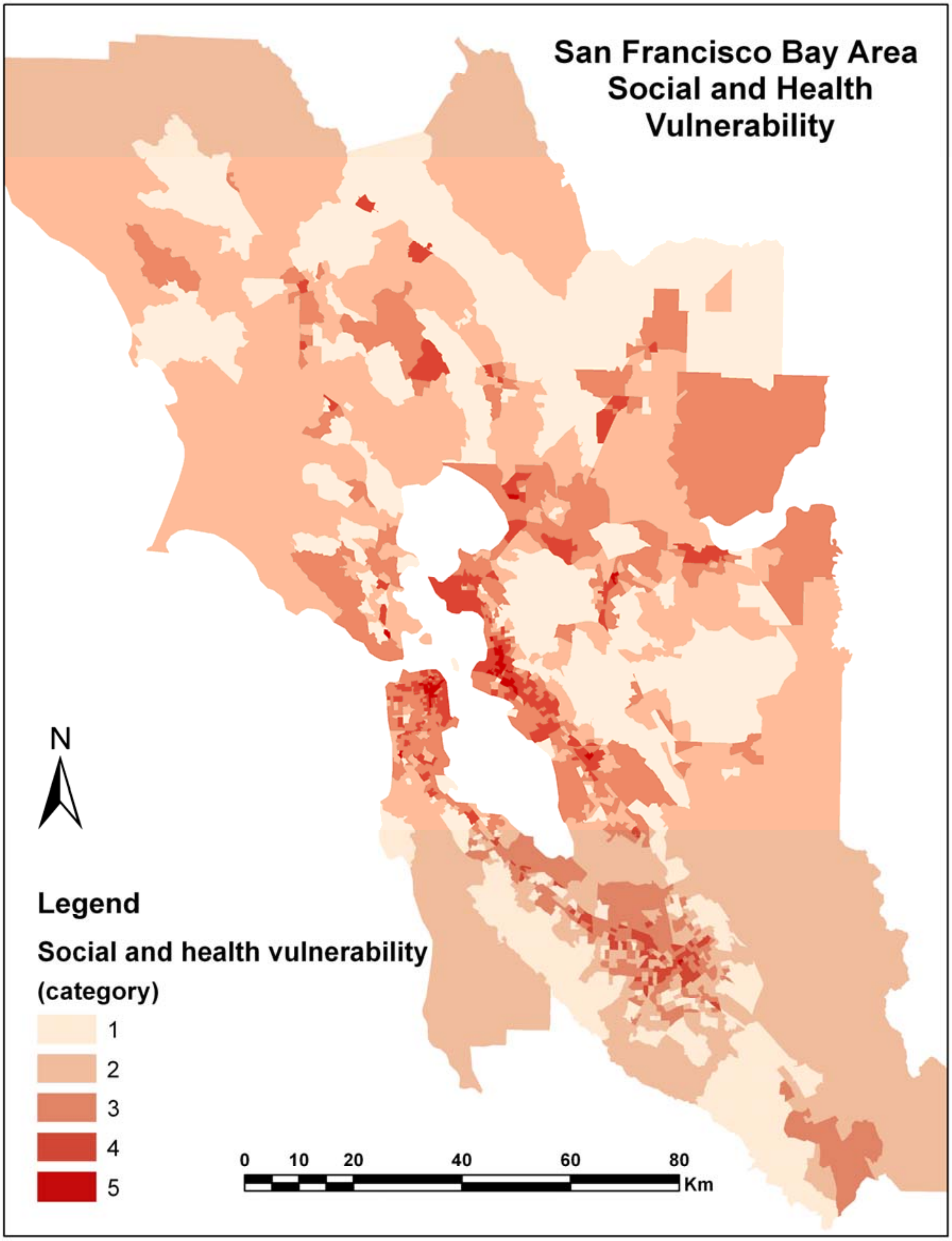


Figure 29c. Social and Health Quintile Scores at the Tract Level in the San Francisco Bay Area

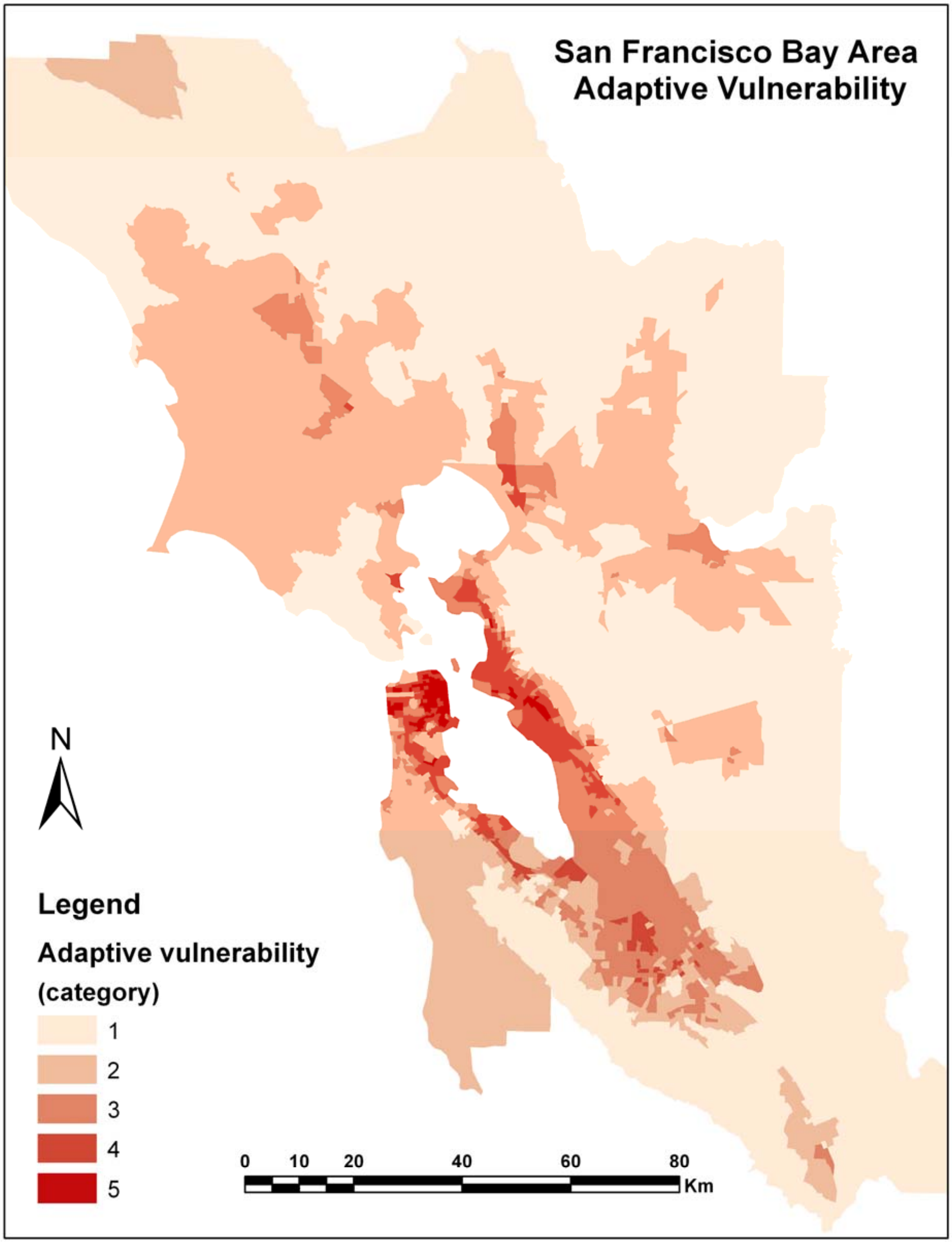


Figure 29d. Lack of Climate Change Adaptive Capacity Quintile Scores at the Census Tract Level in the San Francisco Bay Area

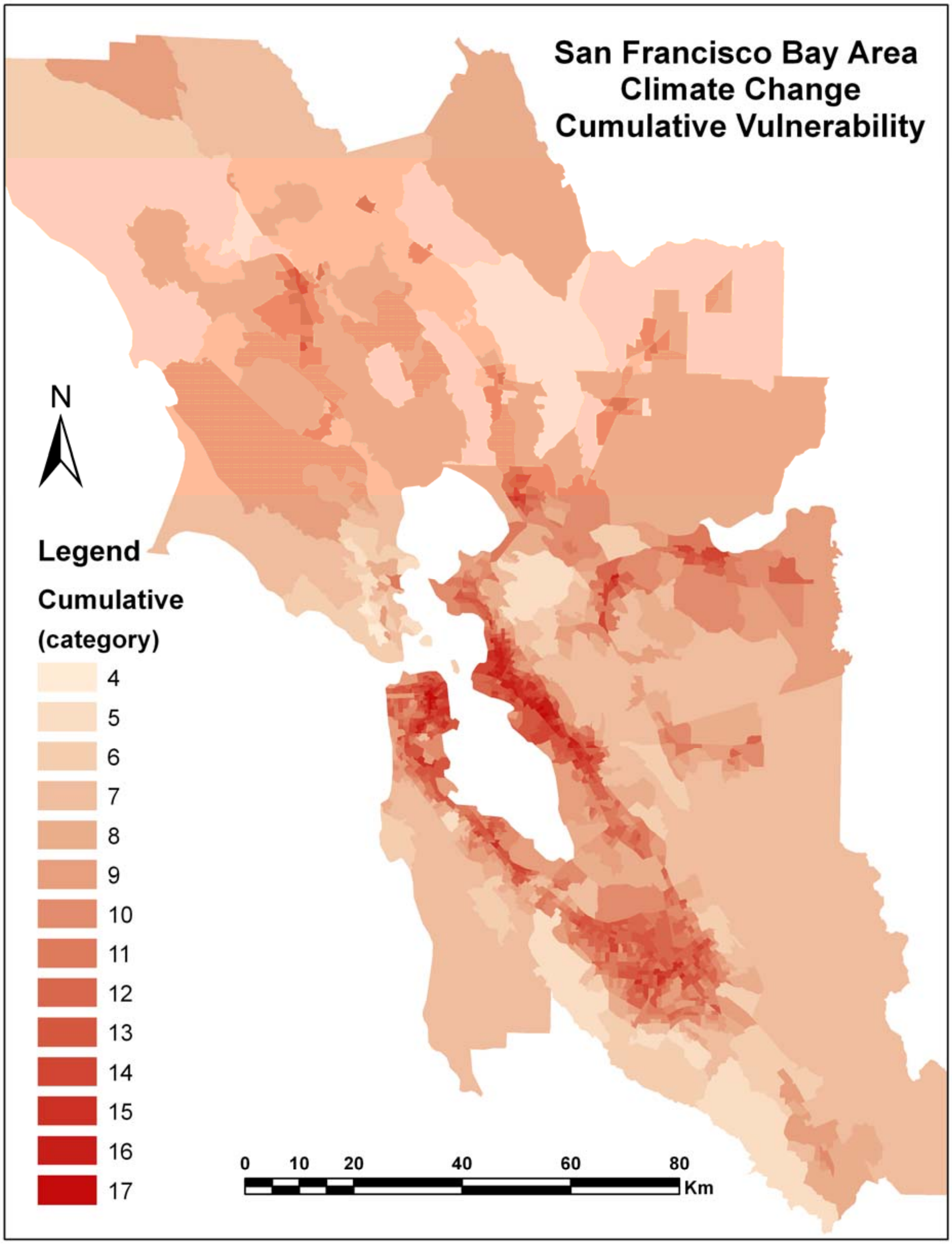


Figure 29e. Cumulative Quintile Scores at the Census Tract Level in the San Francisco Bay Area

Fresno Region

Figures 30a–e display the EJSM maps for the Fresno region. Similar to the EJSM maps shown for the San Francisco Bay Area, a higher value indicates a greater vulnerability.

The map showing vulnerability to heat stress for Fresno county demonstrates higher vulnerability in the downtown area of the city of Fresno (Figure 30a). The higher heat stress calculated from the weather station data may be demonstrated by the urban heat island effect; whereby, areas with higher impervious surfaces and lower tree canopy have higher temperatures. This is shown with the central city of Fresno also having higher vulnerability for Category 4, adaptive capacity (Figure 30d), which includes tree canopy and impervious cover. However, the western part of Fresno county also demonstrates higher vulnerability in lack of adaptive capacity. A similar pattern of higher vulnerability in downtown Fresno and the western part of the county is shown for social and health vulnerabilities (Figure 30c), indicating that areas that have less adaptive capacity and higher heat stress are also where more vulnerable populations live—particularly those with greater elderly populations living alone and those without access to a car. The air pollution vulnerability map also demonstrates that downtown Fresno is the area with greatest air pollution exposures in Fresno County (Figure 30b). Cumulatively, the areas that are most vulnerable in Fresno county are the downtown areas of the city of Fresno and some rural areas in the western part of the county (Figure 30e).

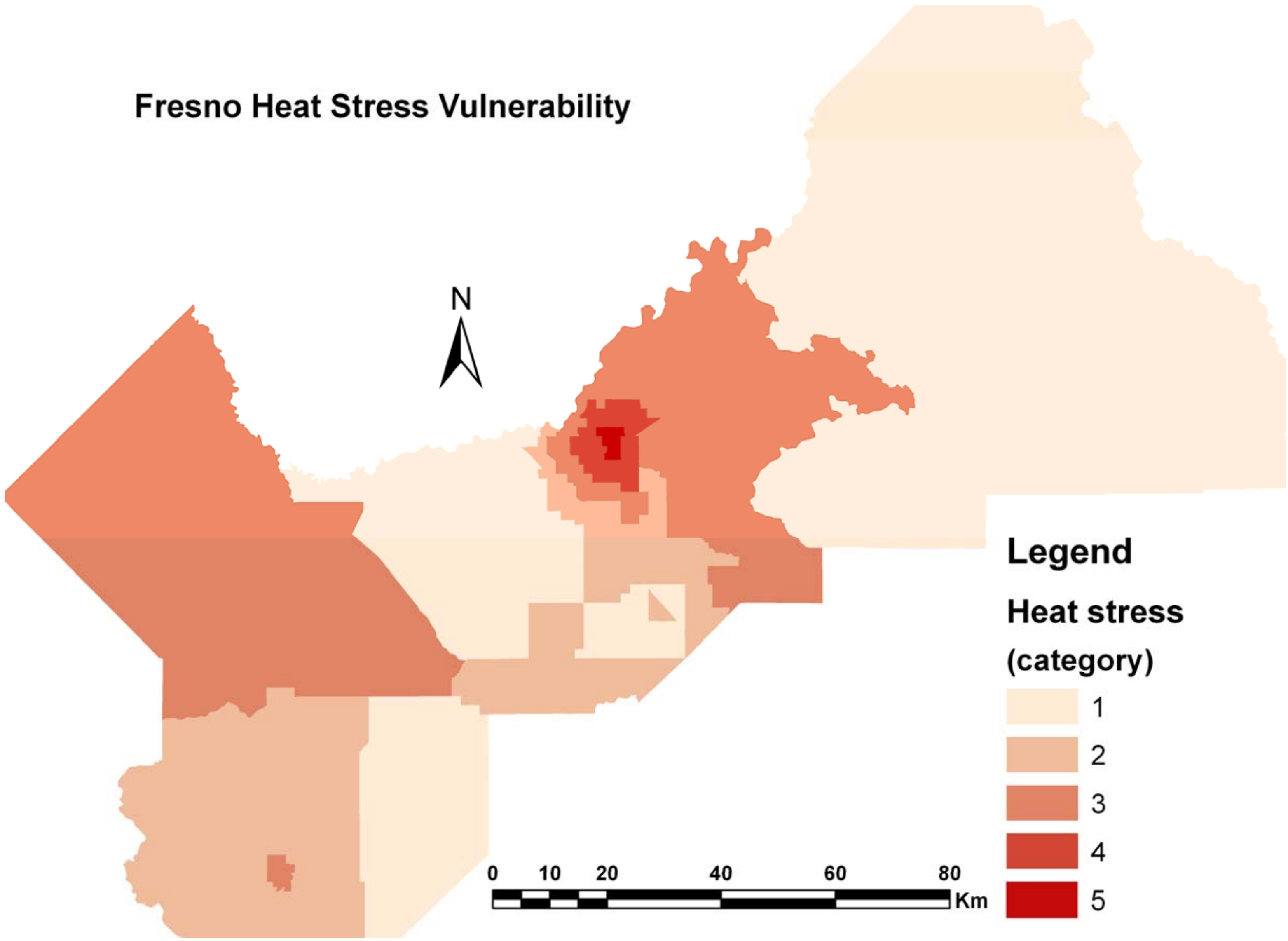


Figure 30a. Heat Stress Quintile Scores at the Census Tract Level in Fresno County

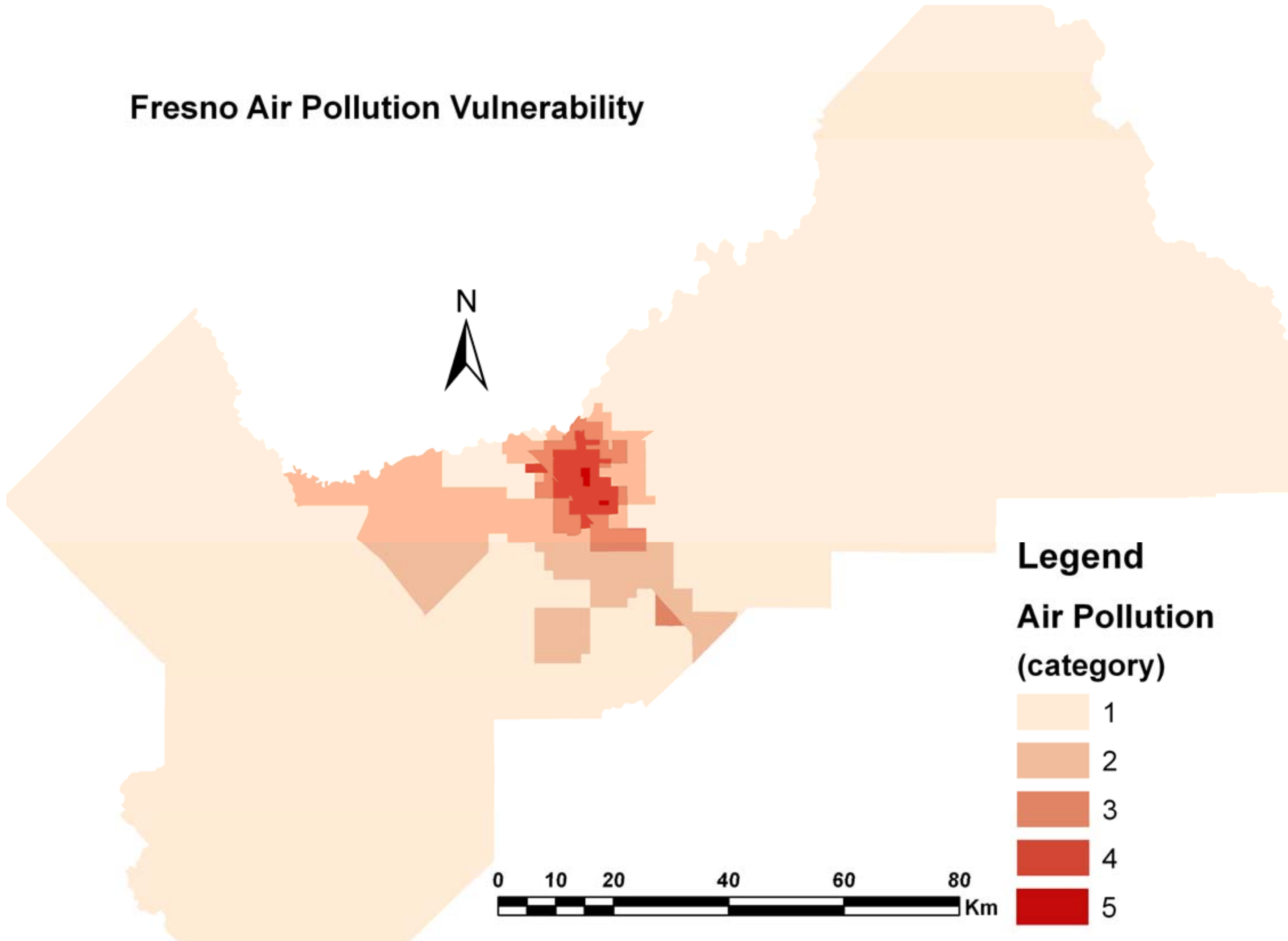


Figure 30b. Air Pollution Quintile Scores at the Census Tract Level in Fresno County

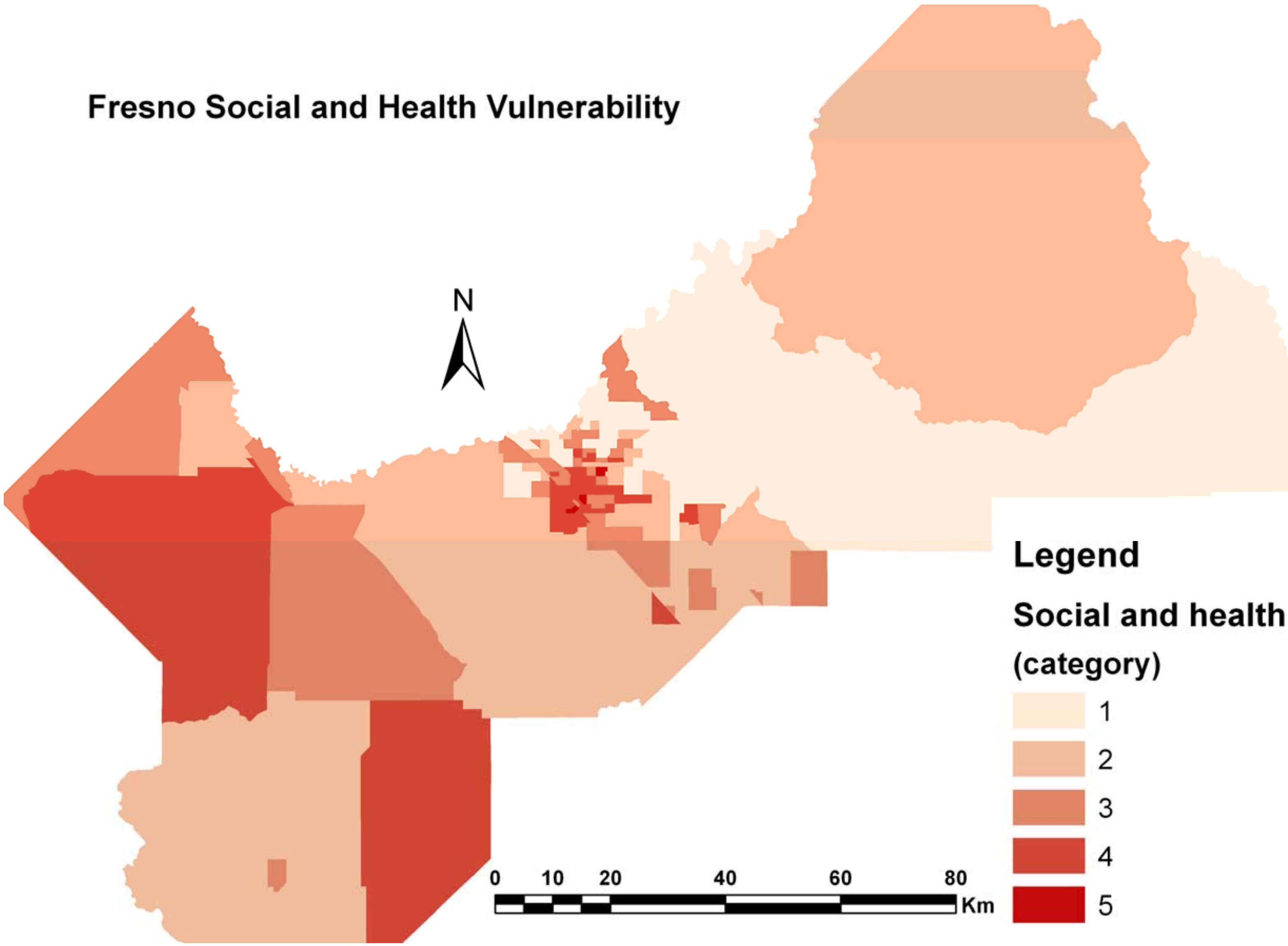


Figure 30c. Social and Health Quintile Scores at the Census Tract Level in Fresno County

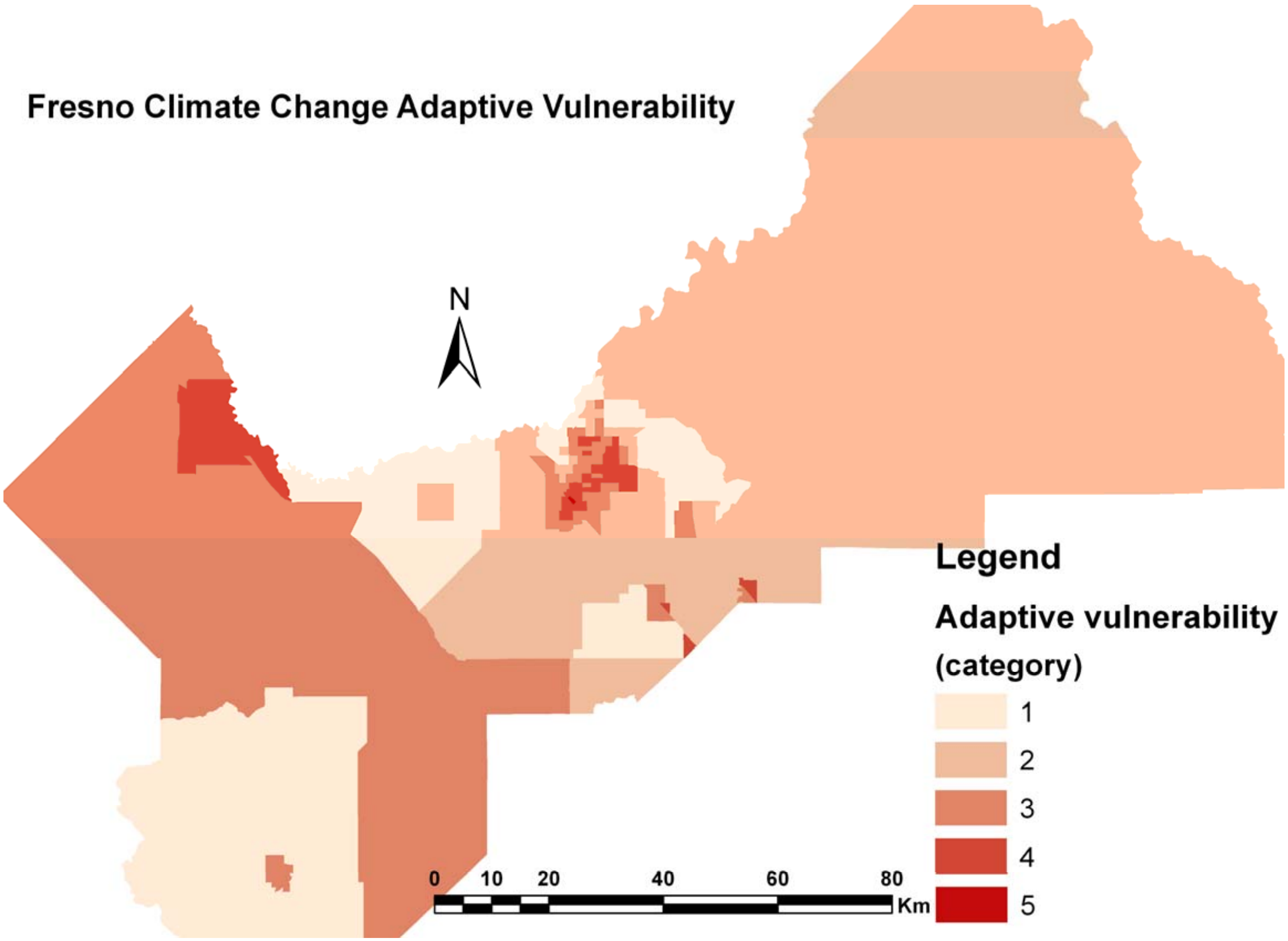


Figure 30d. Lack of Climate Change Adaptive Capacity Quintile Scores at the Census Tract Level in Fresno County

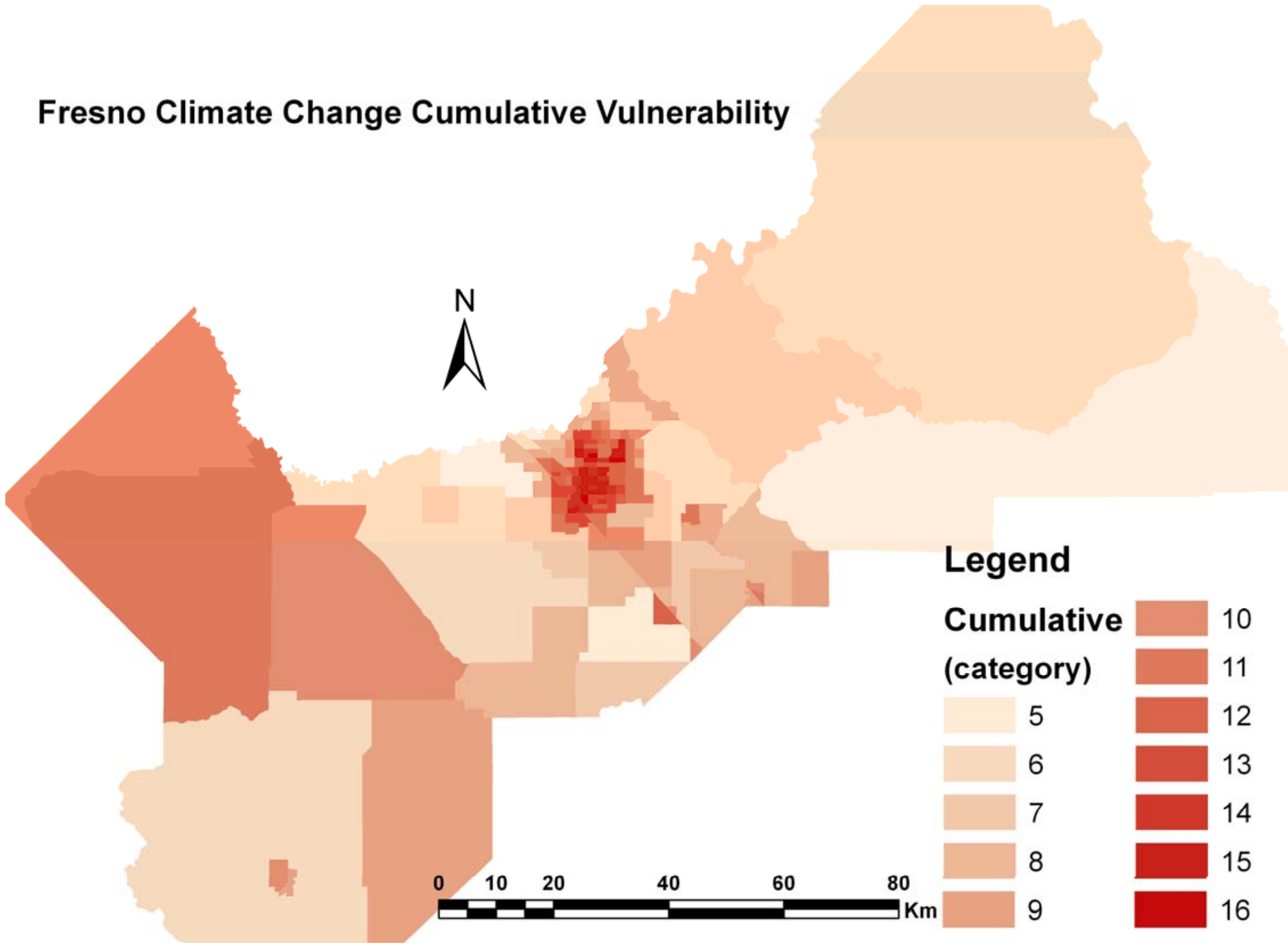


Figure 30e. Cumulative Quintile Scores at the Census Tract Level in Fresno County

Future Directions for Vulnerability Analyses

In estimating absolute heat stress, we used apparent temperature above 40°C (104°F) as an indicator for heat stress. In reality, mortality from heat stress could occur well below 40°C. Other extreme temperature measures should be tested for specific purposes. We used % elderly living alone rather than only the % elderly because those living alone would have greater difficulty in being transported to protection centers where air conditioning is available.

Car ownership was used as an indicator of resources available for avoiding heat stress. Infrastructure of public transport could be used as an indicator for such purposes; however, because of difficulty in retrieving such data, car ownership was used instead. Public transport data should be applied if such data are available.

We used diesel PM, $PM_{2.5}$, and NO_2 rather than ozone (O_3) in modeling air pollution was because we were more interested in local emission sources and small area variation of pollutants. Ozone is a secondary pollutant, and it is not emitted directly by combustion sources, but formed by complex photochemistry. We were unable to obtain or derive O_3 estimates for small areas, and therefore could not include it in this analysis, but this pollutant warrants inclusion for future analysis because it has been implicated with climate change and is also a powerful climate forcing pollutant (Smith et al. 2009).

Global climate change will contribute not only to an increase in extreme heat events and air pollution, but also to an increase in wildfires, coastal flooding, and erosion in California. Information on wildfires and coastal flooding and erosion were not added to our framework to assess climate change and adaptation inequality. However, future extension of the framework could use CalFire publications on Fire Hazard Severity Zones for the current extent and severity of wildfires in California. Flood risk inundation maps for the California coast developed by the Pacific Institute (Pacific Institute 2009) could be incorporated into our framework to show the areas at risk from a 100-year flood event following a 1.0 meter (39 inches) and 1.4 meter (55 inches) rise in sea levels (A2 and B1 scenario, respectively).

Forecasting future scenarios were not included in the present study; however, future studies could include these scenarios using downscaled climate change models such as the method of Hidalgo, Dettinger, and Cayan (documentary background of this method in http://cascade.wr.usgs.gov/data/Task1-climate/gridded_data_US/supporting_materials/CEC-500-2007-123.pdf). For example, future air quality data could be based on downscaled climate model output from National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM). Future wildfire risks could be added from projections by the 2011 California Climate Change Center studies by Krawchuk and Moritz (2011). Providing scenarios of future vulnerability can make us better prepared to protect communities of the most vulnerable.

Generally, weather stations are placed at a distance of at least four times the height of the nearest building (or any wind obstruction) for ground installation or at least six feet above the roof line for rooftop installation. These efforts are meant to measure air temperature and reduce the impact from ground features. By contrast, land surface temperature is a measurement of how hot the land is to the touch. It differs from air temperature because land heats and cools more quickly than air. Heat island was not accounted for in our assessment of heat stress; however, this could be addressed by using surface temperature derived from remote sensing data. Thus we used satellite data to create models of the land surface temperature at 30 meter resolution, which can provide a measure of small-scale variations in the urban heat island. We believe that this can inform an understanding of small-area variations in air temperature throughout an urban area. This method will require more resources than were possible from this project, such as an extensive temperature monitoring campaign that would allow ground-truthing of this novel model. This section presents our preliminary work and discusses how we propose to further investigate this in future research.

Modeling Summer Heat Stress Using Land Surface Temperature

Because lighter-colored materials such as grass, trees, and soil are more reflective of sunlight (higher albedo) while darker materials such as roads, buildings, and other surfaces are more absorbent of heat (lower albedo), we created surface temperatures for the San Francisco Bay Area and Fresno to reflect the small area variation (at a 30 m resolution) of land surface temperature in these two regions. The surface temperature is estimated as described by the procedures described below.

Landsat Thematic Mapper (TM) data for the summer of 2010 were acquired from the United States Geological Survey (USGS) for the study regions. The TM data used in our analysis include three visible and three infrared bands, all with a spatial resolution of 30 m and a thermal band with 60 m resolution. These images were orthorectified by the USGS, the root mean-square error (RMSE) of the rectification was less than a pixel, and the imagery was not atmospherically and topographically corrected. Below we outline the procedures for turning the satellite data into a model of land surface temperature.

Procedure A: The pixel digital numbers (*Q*) in the thermal bands went through a radiometric calibration and were converted to units of absolute radiance by the function given in Chander and Markham (2003):

$$L_\lambda = \frac{LMAX_\lambda - LMIN_\lambda}{Q_{\max} - Q_{\min}}(Q - Q_{\min}) + LMIN_\lambda$$

Q_{max} and Q_{min} were provided by the metadata given by the situation when the data were acquired. $LMAX_\lambda$ and $LMIN_\lambda$ for Landsat TM thermal bands are 15.303 and 1.2378 watts per steradian per square metre per micrometer [W/(m^2.sr.µm)], respectively. The top-of-the-atmosphere radiance, L_λ, that will be used in other steps.

Procedure B: The three visible and three infrared bands were used in a supervised classification system to classify each region into water, dry grass, lawns, forests, urban, and other categories for the San Francisco Bay Area. At least 30 training sets were used for each class, and Figure 31 shows the classification results. Based on emissivity of each land cover type, the classified surface was then transformed into an emissivity surface.

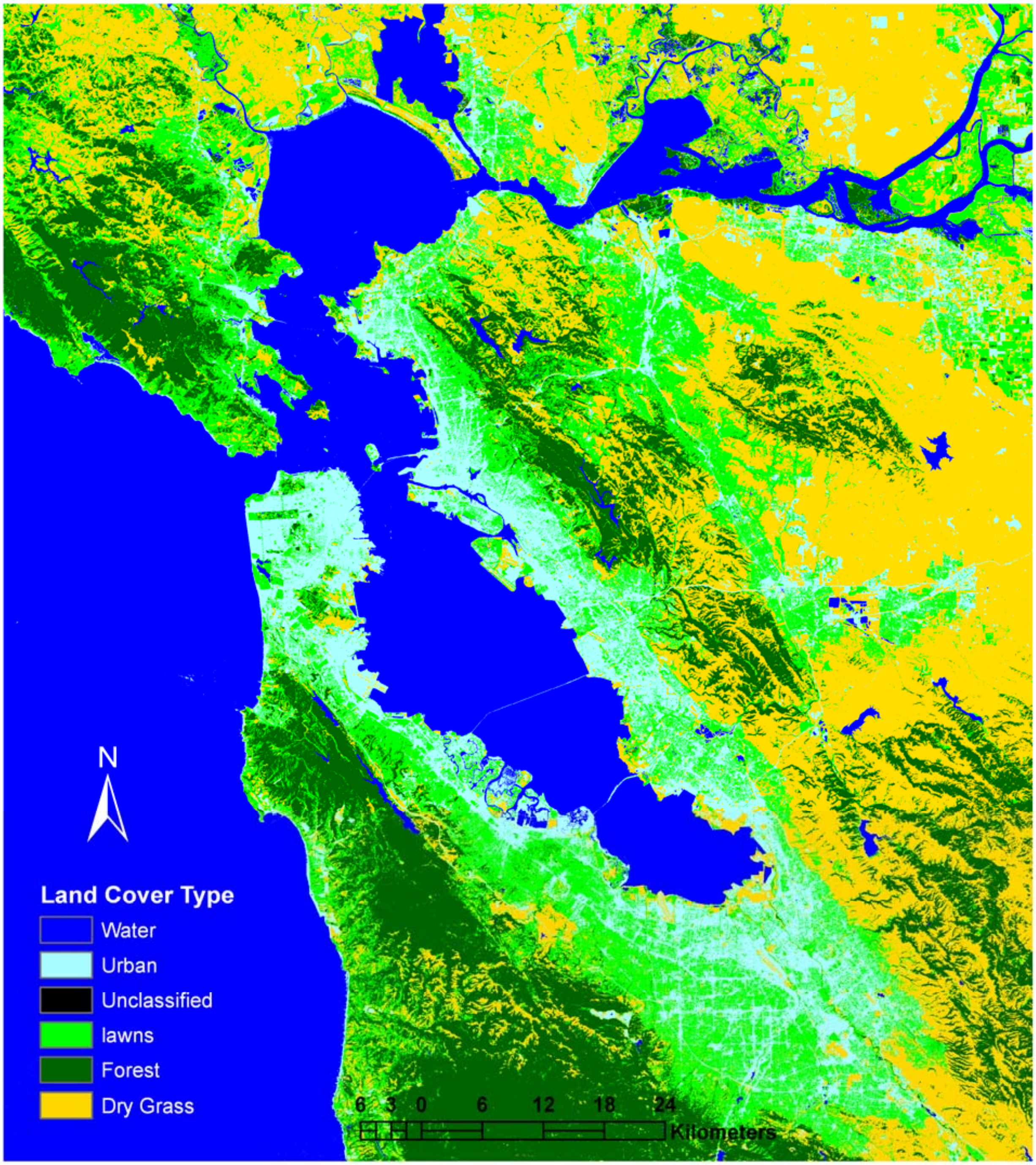


Figure 20. San Francisco Bay Area Land Cover Types Based on Landsat Classification

In Fresno, we encountered problems of differentiating the spectral signatures of fallow fields and urban surfaces. In the future we plan to use multiple images throughout the year to better distinguish between these land types. However, there are many land use classifications that already exist that can be used for this purpose. Therefore, for each region, we used a previously ground-truthed recent land cover classification to also create land surface temperature. For the San Francisco Bay Area, we used the 2006 California Pacific Coast Land Cover Classification created by the National Oceanic and Atmospheric Administration's (NOAA) Coastal Services Center (http://www.csc.noaa.gov/crs/lca/pacificcoast.html). For Fresno, we used the 2005 Central Valley Land Cover Classification by the U.S. Bureau of Reclamation, Mid-Pacific Region. The land use classifications were converted to emissivities by combining many very specific land-use types into the following categories: forests, agriculture, water and wetlands, grass and shrublands, urban areas, barren land, and unclassified. Then we assigned the same emissivity values to these categories as we did to our land use classification based on Landsat TM data in Figure 31.

Procedure C: The top-of-atmosphere radiance derived from procedure A, that which is measured by the satellite and is a full-column measurement, was converted to surface-leaving radiance by removing the effects of the atmosphere in the thermal region. Specifically, an atmospheric correction tool developed by Barsi et al. (2005) and available at (http://atmcorr.gsfc.nasa.gov) for the thermal band of Landsat sensors was applied as follows:

$$L_T = \frac{L_\lambda - L_\mu - \tau(1-\varepsilon)\,L_d}{\tau\varepsilon}$$

where L_T is the radiance of a blackbody target of kinetic temperature T, L_λ is the space-reaching or top-of-atmospheric radiance measured by the instrument, L_μ is the upwelling or atmospheric path radiance, L_d is downwelling or sky radiance, τ is the atmospheric transmission, and ε is the emissivity of the surface, specific to the land cover type. The specific values for T, L_μ, and L_λ were obtained for the specific Landsat Image that was used from http://atmcorr.gsfc.nasa.gov. Radiances are in units of $W/(m^2.sr.\mu m)$, and the transmission and emissivity are unitless. The emissivities were based on our land cover classification in Procedure B and emissivity values from Nichol (2009).

Procedure D: The radiance was converted to surface temperature using the Landsat specific estimate of the Planck curve as follows:

$$T = \frac{K_2}{\ln(\frac{K_1}{L_T}+1)}$$

where T is the surface temperature in Kelvin and K_1 and K_2 are the pre-launch calibration constants 1 and 2, respectively, in Kelvin. For Landsat TM, K_1 = 607.76 and K_2 =1260.56. According to Barsi et al. (2005), with the atmospheric correction, the final apparent surface temperatures have uncertainties less than 2K when the atmosphere is relatively clear.

Figure 32 presents the land surface temperature for the San Francisco Bay Area based on land use classification from our research team using the Landsat TM data. Figure 33 presents the land surface temperature for the same area using the 2006 California Pacific Coast Land Cover Classification. The correlation of surface temperature between the one based on our land use classification using Landsat TM data (Figure 32) and the one based on a pre-made classification (Figure 33) was 0.97. Figure 34 presents the land surface temperature for the city of Fresno based on the 2005 Central Valley Land Cover Classification. The Fresno land surface temperature is only for the city of Fresno at this point but can be updated to include the whole county with additional Landsat tiles.

From these maps, it is clear that the hottest land surface types are found in urban areas, with the land surface temperature map of Fresno demonstrating the hottest temperatures in most of the urban area, as well as the clear diagonal line of Highway 99. In the San Francisco Bay Area, the freeway corridors also demonstrate higher land surface temperatures, and it is possible to delineate within urban areas the suburban and highly urbanized areas.

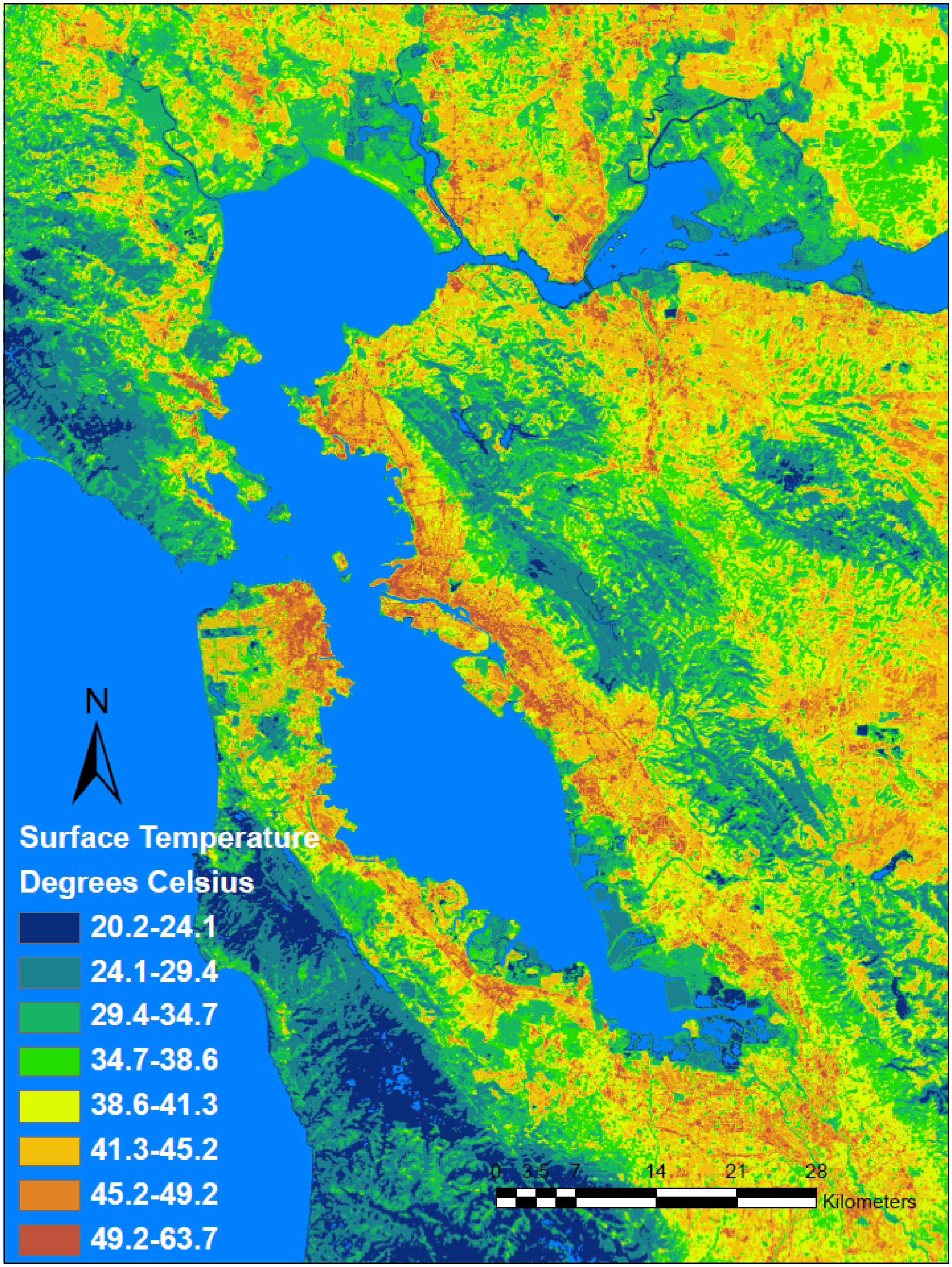


Figure 21. San Francisco Bay Area Land Surface Temperature by Our Research Team Using Landsat TM Data

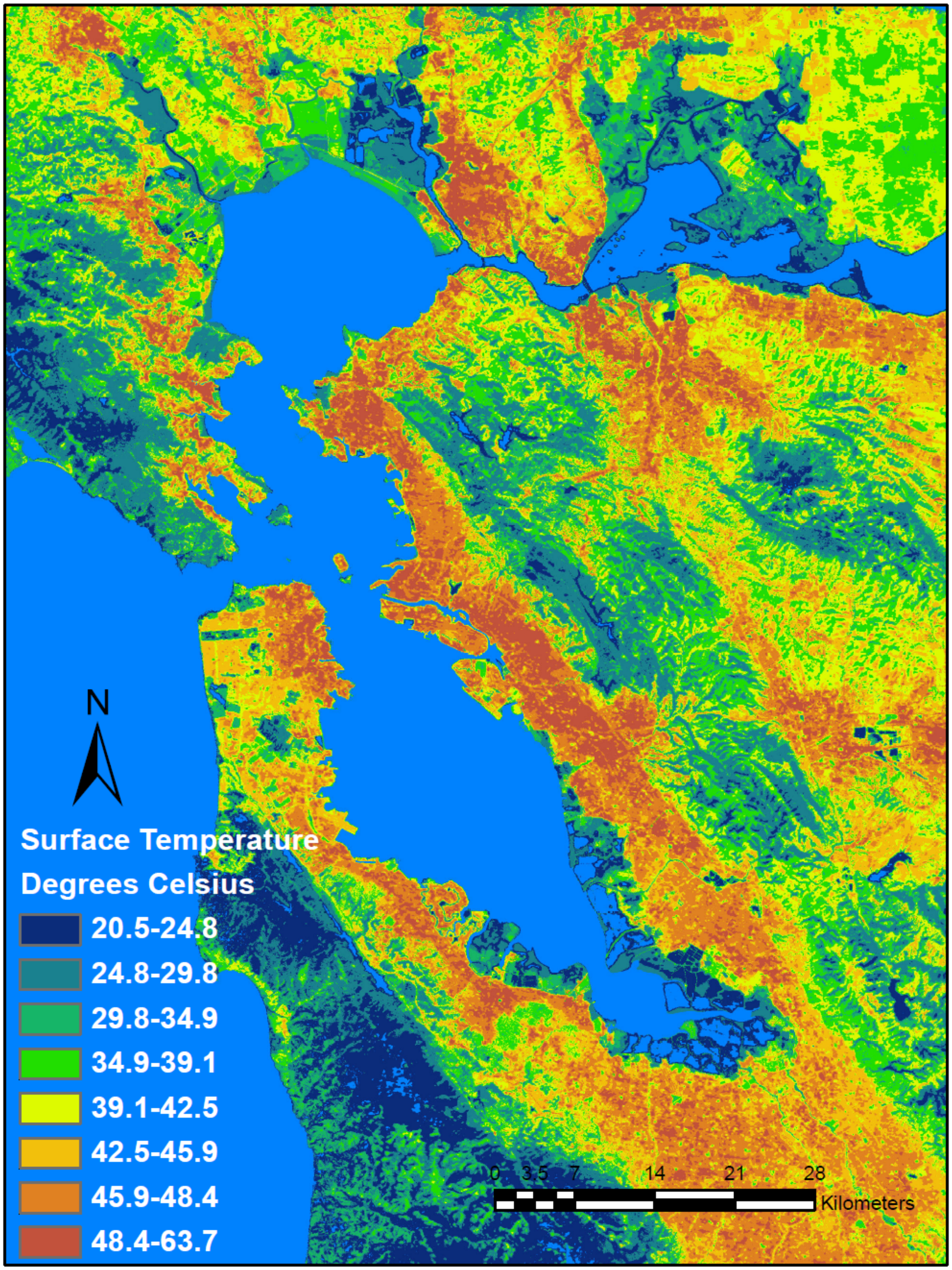


Figure 22. San Francisco Bay Area Land Surface Temperature Based on the 2006 California Pacific Coast Land Cover Classification

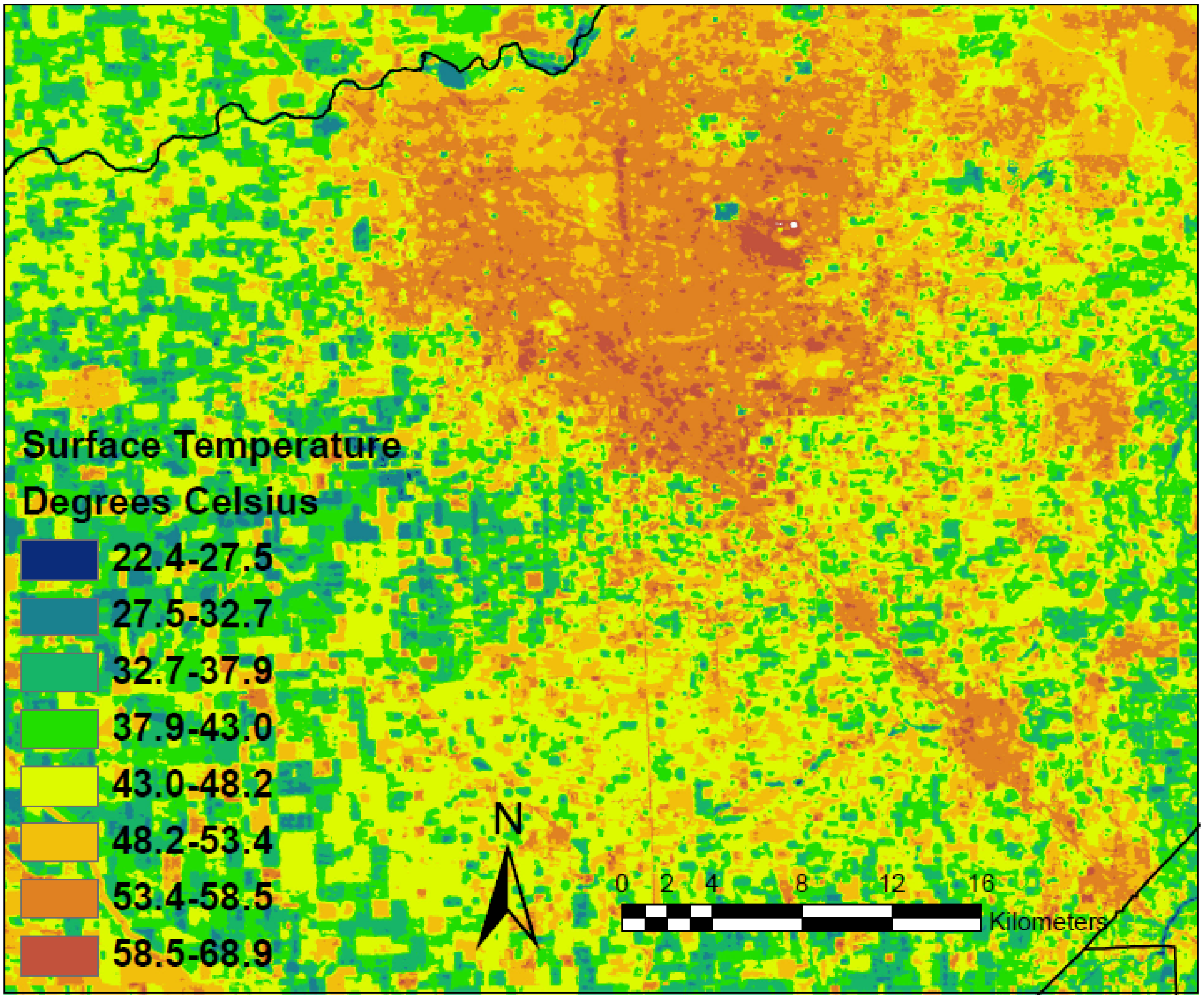


Figure 23. City of Fresno Land Surface Temperature Based on the 2005 Central Valley Land Cover Classification

Estimating land surface emissivity based on the small number of land cover classes apparently ignored the complexity of land surface. For example, all the urban land surfaces were treated as a single class and used one emissivity index. To avoid over-simplifying ground features, we also used emissivity surfaces of 90 resolution provided by NASA Jet Propulsion Laboratory (Hulley et al. 2008). Ahn (2008) found that emissivities retrieved from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at the wavelength region 10.95–11.65 microns (μm) were superior to other bands. Band 14 (wave length 11.3 μm) of the ASTER data was therefore used in our analysis. Figure 35 shows the emissivity surface for the San Francisco Bay Area for 2000–2009 mean.

Repeating procedures A through D by replacing Procedure B with the emissivity surface from Figure 35, we estimated a surface temperature for the San Francisco Bay Area (Figure 36). The scale in Figure 36 is comparable to the surface temperature estimated through land cover classifications but with finer spatial contrasts, especially in urban areas. The proportions with Kelvin temperature below 300 degrees are mainly water.

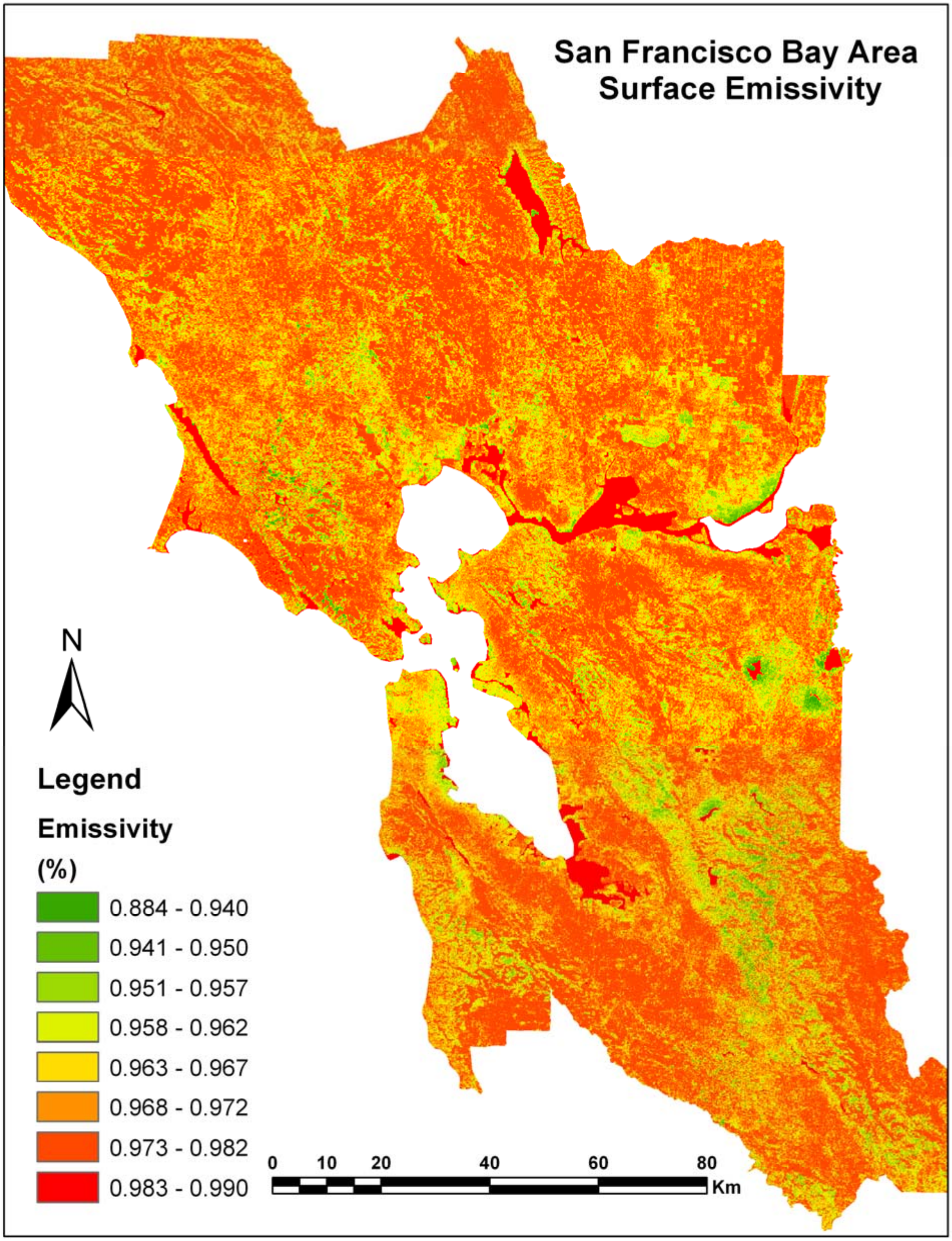


Figure 24. San Francisco Bay Area Surface Emissivities Based on ASTER Data

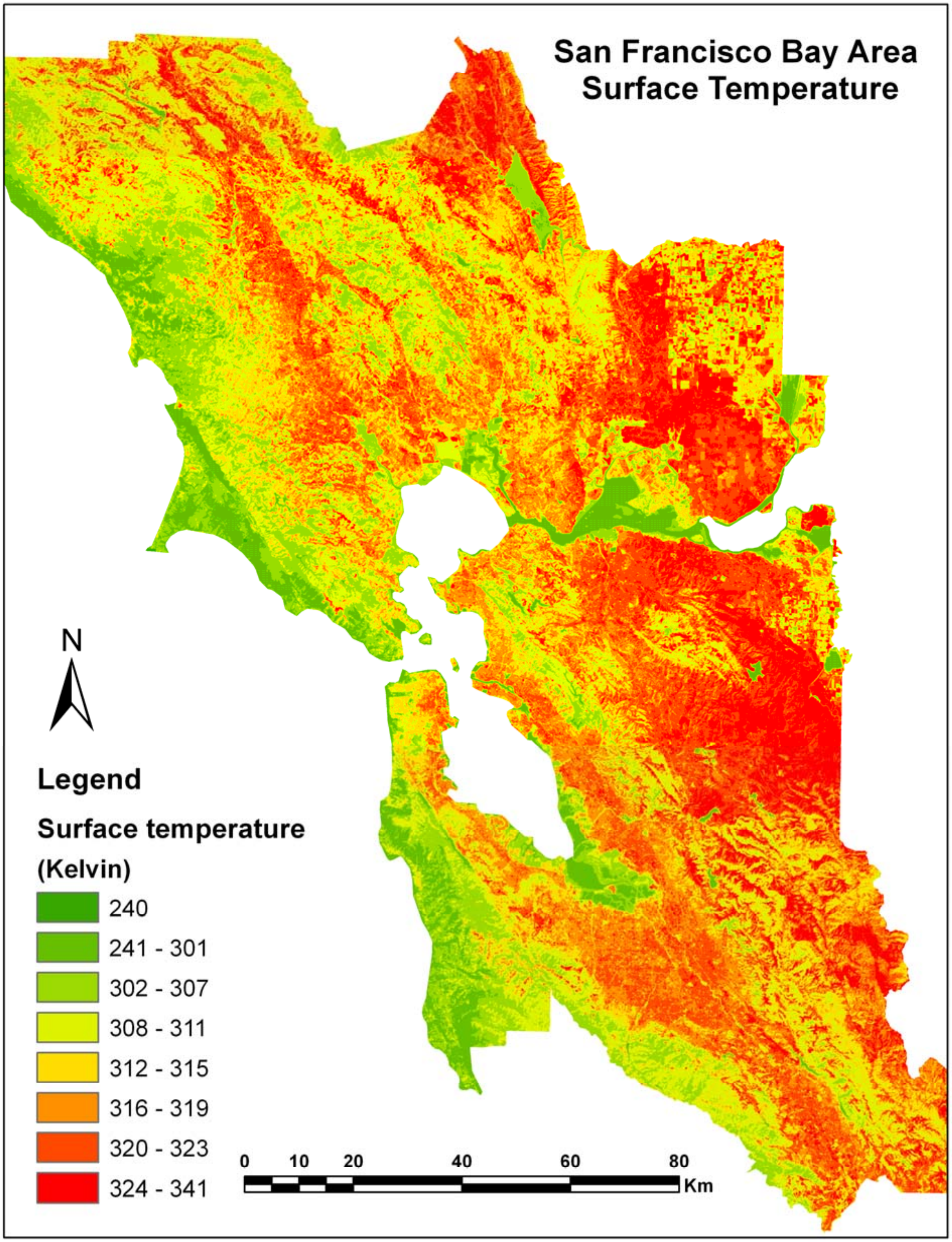


Figure 25. San Francisco Bay Area Surface Temperature Based on NASA Emissivities

Section 3: Conclusions

Based on a conceptual framework and a staged approach, we performed a vulnerability assessment for the San Francisco and Fresno areas. There has been little work on vulnerabilities to climate change focused specifically on the San Francisco Bay Area or Fresno, and our work will help to fill this knowledge gap. Although looking at maps of single vulnerability variables, as we did in Step I, can demonstrate the spatial distribution of a single vulnerability, to plan for climate change, an understanding of the cumulative vulnerability—realizing that vulnerability is a complex structure that involves exposure, susceptibility, and adaptive capacity—is essential. The two methods that we employed to assess the cumulative impacts of vulnerability are complementary and helpful in such an analysis. The CEHII quantifies across a region of whether individual vulnerability variables demonstrate inequality within that region. Once this is known, then the EJSM method allows for identification of the areas within a region that are more vulnerable for a set of vulnerability variables. While the CEHII does not identify the specific geographic areas within a region that are more vulnerable, it allows for the identification of which vulnerability variables are less equally distributed in area. On the other hand, the EJSM allows for the spatial identification of more vulnerable areas for targeting, but because the maps are composites of multiple variables, it does not allow for the identification of which vulnerabilities are more important for a given cumulative exposure category. Therefore, a combination of these two approaches can be very helpful from a climate change adaptation planning perspective.

From the results from the CEHII, there were not many differences between the San Francisco Bay Area and Fresno county as to which variables were most inequitably distributed. In both areas, there was not much inequality related to heat stress, diesel PM showed the greatest inequality of the air pollution exposures, and tree canopy shading was the most unequal of the adaptive capacity variables. Within the social and health vulnerabilities, lack of car ownership and elderly living alone were equally unequal in both regions; however, elderly living alone was more unequal with poverty than with racial composition of the census tracts. This was the only instance in which the curves appeared substantially different between the poverty and racial metrics for the CEHII curves.

The cumulative inequality for both the San Francisco Bay Area and for Fresno County calculated by the CEHII mean that the EJSM can be a useful tool for highlighting areas of greatest vulnerability for targeting adaptation planning. The downtown urban areas for both Fresno County and the San Francisco Bay Area showed cumulatively higher vulnerability than more outlying areas, with the exception of the rural western portion of Fresno County.

This paper does not cover vulnerabilities associated with all adverse health impacts associated with climate change, as mentioned previously. The methods presented in this paper, however, can be applied to those impacts as more information becomes available on their exposures, population susceptibilities and adaptive capacity of communities in the face of those exposures. Additionally, this paper should be revisited and updated as more information becomes available about heat and air pollution exposures, such as detailed downscaled forecasts of climate changes under various future scenarios that are important to public health, and changes such as population demographics, urban design, and air pollution controls that affect susceptibility and adaptive capacity.

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Glossary

AC	air conditioner
ACS	American Community Survey
ADDRESS	A Distance Decay Regression Selection Strategy
AR4	IPCC's Fourth Assessment Report
ASPEN	Assessment System for Population Exposure Nationwide
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CDPH	California Department of Public Health
CEC	California Energy Commission
CEC RASS	California Energy Commission Residential Appliance Saturation Survey
CEHII	cumulative environmental hazard inequality index
CI	cumulative impact
CIMIS	California Irrigation Management Information System
EJ	environmental justice
EJSM	Environmental Justice Screening Method
FPL	federal poverty level
GIS	geographic information systems
HVI	heat vulnerability index
IPCC	Intergovernmental Panel on Climate Change
LUR	land use regression
NASA	National Aeronautics and Space Administration
NLCD	National Land Cover Database
NO_2	nitrogen dioxide
PM	particulate matter
$PM_{2.5}$	particulate matter with an aerodynamic diameter less than 2.5 μm
NCDC	U.S. National Climate Data Center
NCAR	National Center for Atmospheric Research
PCM	Parallel Climate Model

RMSE	root mean-square error
SES	socioeconomic status
SoVI	Social Vulnerability Index
TM	Landsat Thematic Mapper
UCSB	U.S. Census Bureau
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VIF	Variance Inflation Factor

Appendix A: Review of Peer-Reviewed Research, Government Documents and Grey Literature on Climate Change in California

This section summarizes the existing work that has been done investigating climate change impacts on public health and possible adaptation in the Bay Area.

In 2006, Steiner et al. applied complex climate models to forecast the changes in ozone concentration for central California (Steiner et al. 2006). These models included data on anthropogenic emissions of NO_x, CO, and VOCs (as well as biogenic emissions of VOCs), temperature, absolute humidity, and boundary conditions. For all simulations, the San Francisco Bay Area was predicted to have increased levels of ozone by 2050. This effect was on average 1–2 percent greater compared to anywhere else in the study area. When the researchers incorporated a variable for a predicted 80 percent reduction in emission factors (due to technological advances), the net ozone change for the Bay Area was zero. They conclude that mitigation impacts in the form of decreasing emissions are necessary for the Bay Area to avoid large increases in ozone concentration under likely scenarios of climate change.

In 2009, Reid et al. investigated heat waves and vulnerability in 39,794 U.S. census tracts (Reid et al. 2009). Population vulnerability was based on 10 variables (diabetes, below poverty line, race other than white, live alone, age >= 65 and living alone, age >= 65, less than a high school diploma, not green space, no central air conditioning (AC), no AC of any kind), of which 4 variables explained more than 75 percent of the variability: social/environmental vulnerability (combination of education, poverty, race, and green space), social isolation, AC prevalence, and proportion of elderly/diabetic. Based on their analysis, San Francisco metropolitan statistical area was the most vulnerable region, mainly due to the lack of air conditioning in the region's housing units. While this study does not specifically look at variability within the Bay Area, it highlights the impact that increasing temperatures will have on the region and how the region is particularly vulnerable to this type of impact.

Sadd and colleagues have developed an Environmental Justice Screening Method (EJSM) (Sadd et al. 2011), which was originally applied to the South Coast Air Basin in Southern California but is now also being applied to the Bay Area and other regions The EJSM was developed as an approach for assessing patterns of cumulative impacts from environmental and social stressors across neighborhoods within regions, using Southern California as a case study. Using secondary data sources, the EJSM evaluates, integrates and scores multiple metrics of environmental and social stressors to rank census tracts in a way that is both scientifically valid, yet transparent to diverse stakeholders, particularly policymakers and communities. Twenty-four metrics are organized into three indicator categories: (1) hazard proximity and land use; (2) air pollution exposure and estimated health risk; and (3) social and health vulnerability.

Screening methods such as the EJSM can help regulators and policy makers more efficiently target their efforts to remediate cumulative impacts, environmental inequities, and more effectively focus regulatory action at the neighborhood level. Currently, the burden of proof is placed on communities to demonstrate the cumulative impacts of environmental and social stressors and push for action. Cumulative impact (CI) screening such as the EJSM provides environmental policy and programs with a more proactive approach that removes this burden from vulnerable communities so that those without an active environmental justice movement or capacity for civic engagement can also receive regulatory attention and protection. Moreover, the EJSM can advance regulatory decision-making and the implementation of environmental policies. In California, the Global Warming Solutions Act of 2006 (AB 32) (2006) mandates statewide goals to reduce greenhouse gas emissions and also requires consideration of how the law's implementation will affect "communities that are already adversely affected by air pollution." Moreover, the law requires that measures to reduce greenhouse gas emissions must be designed to "direct public and private investment toward the most disadvantaged communities in California and provide an opportunity for small businesses, schools, affordable housing associations, and other community institutions to participate in and benefit from statewide efforts to reduce greenhouse gas emissions."

So far, this screening method has been applied to Southern California and is being expanded to other California regions, including San Diego, the Central Valley, and the San Francisco Bay Area. Mapping the intermediate EJSM scores for the three indicator categories at the census tract level reveals some interesting geographic patterns. The maps shown below cover only the South Coast Air Quality Management District (SCAQMD) portion of the Southern California region studied, and preliminary results for the Bay Area. In Southern California, areas with high hazard proximity and sensitive land use scores (Figure A1) tend to correspond with the more densely populated areas, and follow major transportation corridors. High scores are typical in areas with populations characterized by high-minority, low-income populations, and adjacent to sectors of concentrated industrial activity (shown in dark gray), such as the Ports of Los Angeles/Long Beach, the Los Angeles International Airport, and the industrial core of Los Angeles running from the ports to downtown.

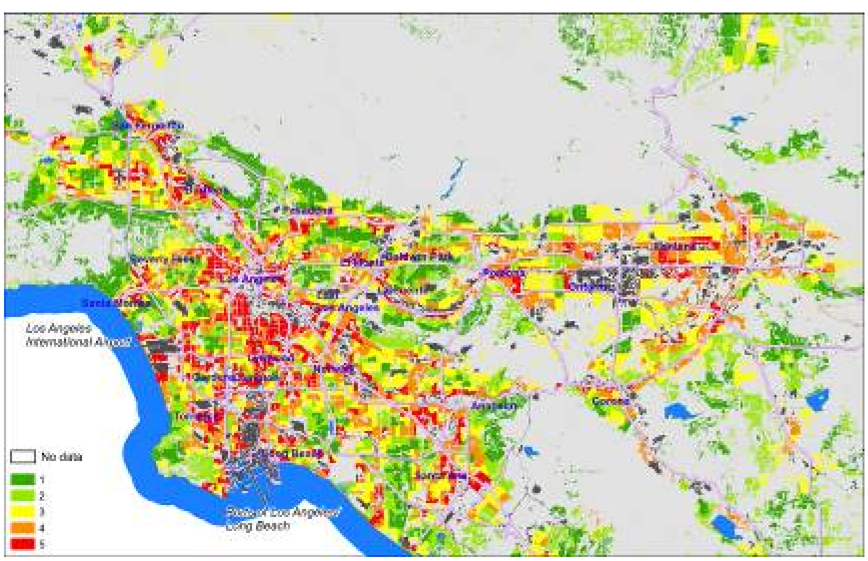

Figure A1: Hazard Proximity and Sensitive Land Use Quintile Scores at the Tract Level (Mapped on CI Polygons) – South Coast Air Quality Management District (SCAQMD), California

The geographic distribution of Health Risk and Exposure scores (Figure A2) is less complex, but with a clear concentric pattern with little fine-scale variation with broad areas with a single score. Areas with the highest scores surround heavily industrialized areas, including Central and East Los Angeles, the Alameda corridor connecting downtown to the ports along the 710 transportation (truck, rail, freeway) corridor, and the industrial centers in Baldwin Park and east of Ontario International Airport. Coastal and foothill neighborhoods are characterized by low scores, and the apparent effects of the freeway system on the overall pattern are minor.

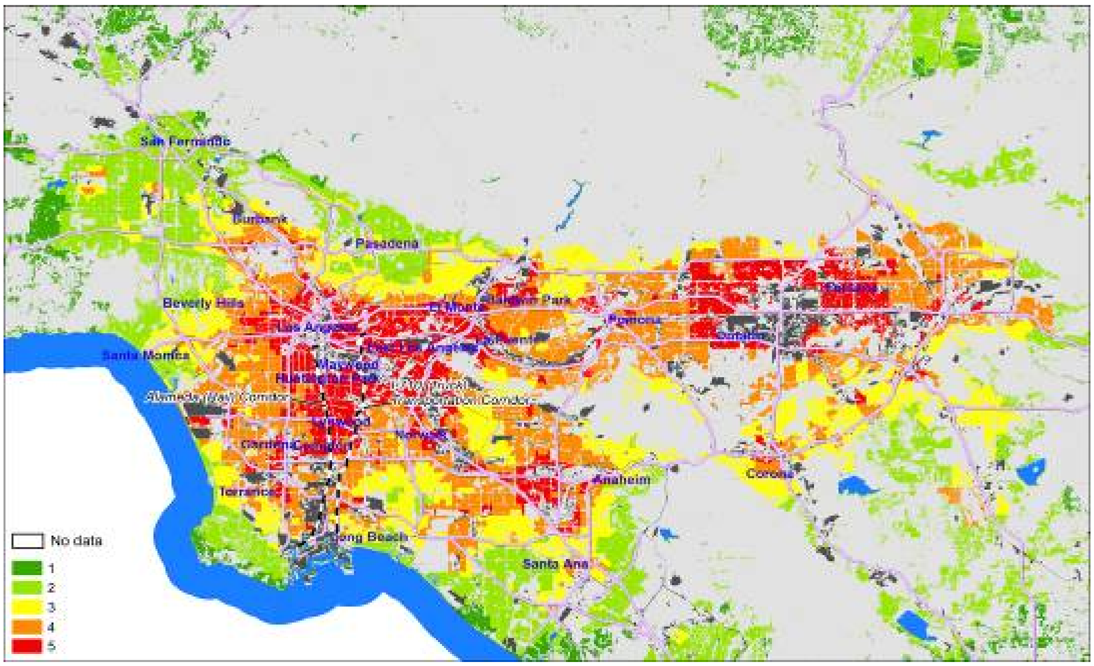

Figure A2: Air Pollution Exposure and Health Risk Quintile Scores at the Tract Level (Mapped on CI Polygons) – SCAQMD

Social and Health Vulnerability scores (Figure A3) reflect the well-documented pattern of residential segregation in metropolitan Los Angeles by socioeconomic status (SES) variables of race and class. Many of the same neighborhoods bearing the burden of high exposure to air pollution and its attendant health risks are also those where the most vulnerable populations are also concentrated.

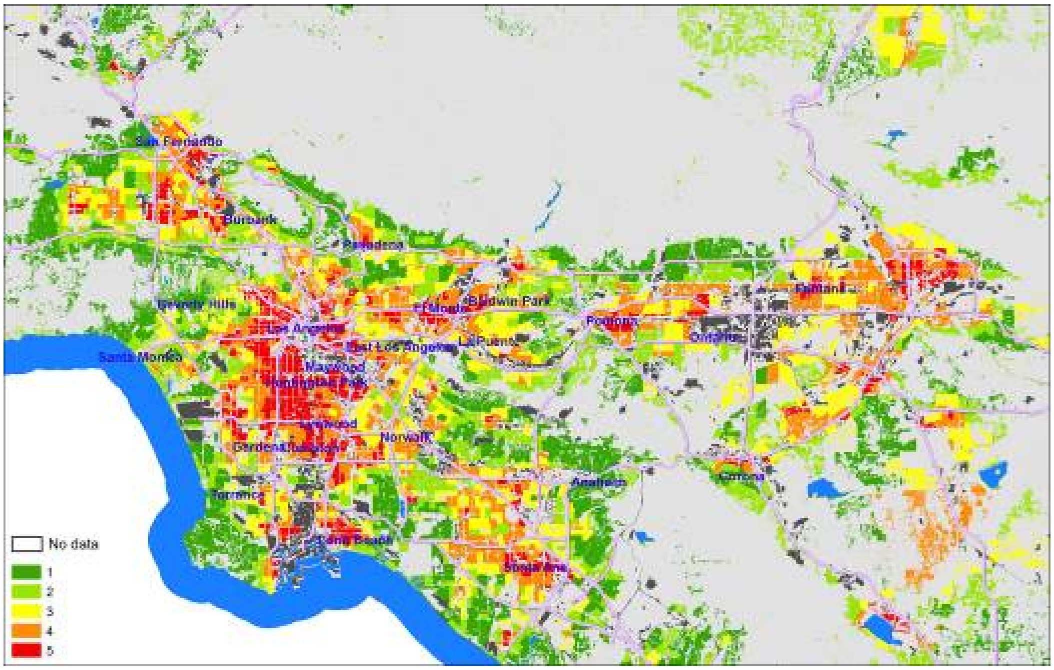

Figure A3: Social and Health Vulnerability Quintile Scores at the Tract Level (Mapped on CI Polygons) - SCAQMD

The three indicator category scores (hazard proximity, air pollution exposure, and health risk and social/health vulnerability) are then combined into a Total CI Scores that ranges from 3 to15 (Figure A4). For visual representation, these scores are attached in the GIS system to each CI polygon (since that focuses attention on the residential and sensitive land use areas), but they are based on tract-level scores. It is worth noting that the regional distribution of Total CI Scores is near normal.

Certain areas, like communities near the ports and airports, as well as the heavily impacted Pacoima neighborhood in the San Fernando Valley, have the highest CI scores (shown in red). Community activism around environmental justice has occurred in these areas and they are often receiving targeted attention from regulators and policy makers. What is perhaps more useful is that the CI map also points to communities that do not have a record of organizing and have not brought themselves to the attention of regulators or decision-makers, such as East Los Angeles (which is intersected with freeways and populated with smaller hazard), Pomona east of Los Angeles, and parts of the Inland Valley (Riverside and San Bernardino Counties). From the view of regulators, the map helps direct attention to places where specific attention may be needed to address environmental health concerns not usually considered; from the point of view of community stakeholders, the map highlights locations where residents may need to be educated and engaged to address environmental hazards.

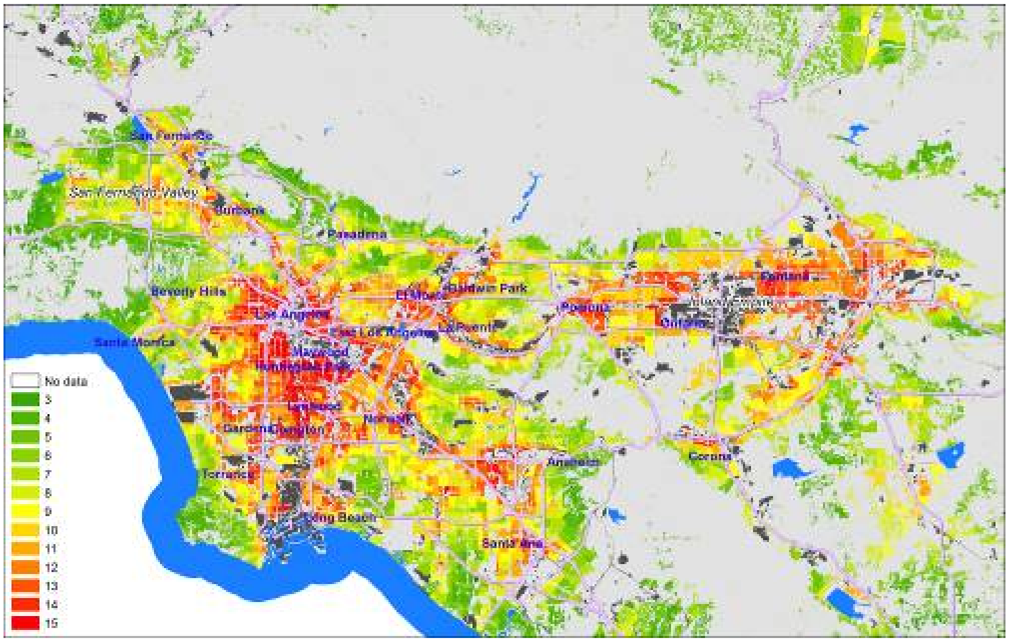

Figure A4: Total Cumulative Impact Quintile Scores at the Tract Level (Mapped on CI Polygons) – SCAQMD

Government Reports: Summary

In addition to the peer-reviewed literature and our ongoing work, government reports were also reviewed. Climate change adaptation reports and simulation models relevant to the San Francisco Bay Area range broadly in geographic scope. California has multiple layers of adaptation work delegated to all levels of government structures which include city, county, regional, and state agencies. The multi-layered framework allows California and its unique geographies to respectively respond to climate change issues relevant at the local micro-scale or the statewide regional scale. While adaptation concerns local geographies, it is based on global and macro-regional predictive simulations since decadal and centennial forecasts do not have the resolution capacity for predicting microclimates (IPCC 2007).

Who is working on Climate Change?

Current efforts in the San Francisco Bay Area have been recently summarized in the write-up summary of presentation "Climate Change Adaptation Efforts at the State and Bay Area Regional Levels" Planning for Climate Change Workshops (Schuchat et al. 2009). These include a proposed amendment of the San Francisco Bay Plan to include climate change adaptation policies, the Adaptation Assistance Program, the Regional Sediment Management Program, the Rising Tides Design Competition, and the San Francisco Estuary Project.

The following organizations each have been working on climate change adaptation from their respective geographical scope and interest (fiscal, environmental, health) and are of interest to the San Francisco Bay Area.

- San Francisco Bay Conservation and Development Commission (BCDC)[2]
- State of California
- California Department of Public Health (CDPH)
- U.S. Environmental Protection Agency (EPA)
- Department of the Interior (DOI)
- U.S Government
- National Academy of Sciences' National Research Council (NAS-NRC)
- Intergovernmental Panel on Climate Change (IPCC)
- Pew Center on Global Climate Change
- Pacific Institute
- Public Health Institute (PHI)
- California Environmental Justice Alliance (CEJA)

California Climate Change Adaptation and Executive Order S-13-08 by the California Governor

In 2008, Governor Arnold Schwarzenegger issued Executive Order S-13-08, which commissioned the California Sea Level Rise Report under the auspices of the National Academy of Sciences. It furthermore directed the California Resource Agency to create the 2009 California Climate Adaptation Strategy Report (California Natural Resources Agency 2009). Together, these two reports have had a strong influence on the direction of climate adaptation work in the State of California. According to the California Climate Adaptation Strategy Report, the most relevant sector for the Bay Area is the Ocean and Costal Resources.

California Climate Action Team

The California Climate Action Team (CAT) is composed of a number of state agencies and is led by the Secretary of CalEPA to "coordinate the statewide efforts to implementing the global warming emissions and the state's Climate Adaptation Strategy" (http://www.climatechange.ca.gov/). The CAT reports its work to the governor every two years. The most recent report is the 2009 Climate Action Team Report to the Governor and Legislature (published March 2010) (Climate Action Team 2010).

[2] BCDC is the primary driver of Climate Change Adaptation in the San Francisco Bay Region, but other local agencies are also working on climate change adaption and are described in more detail below.

The Climate Change Adaptation Report General Framework

Climate change affects practically every aspect of the Earth, many of which are relevant to human, plant and animal wellbeing. Using the IPCC Fourth Assessment Report as an example, generally speaking, the current work on climate change organizes the effects in the following sectors: (1) water, (2) agriculture, (3) infrastructure/settlement (including coastal zones), (4) human health, (5) tourism, (6) transport, and (7) energy; and the following categories of impact: (1) water, (2) ecosystems, (3) food, (4) coast, (5) health, and (6) singular events. While not all of these have direct impacts on human health, all are related to human well-being and quality of life (IPCC 2007).

Climate Change Simulation

Climate change simulation is limited in resolution, given that the climate change contribution to microclimates is difficult to predict for longer time scales. High fidelity for simulations is still mostly limited to the continental scale, but local data are rapidly improving the ability of models to fine tune to smaller regions. The best summary of climate change models is found in the IPCC fourth report (2007) of Workgroup I, *The Physical Science Basis,* Chapter 8: Climate Models and Their Evaluation. The fifth report is under way. The primary models used are based on Atmosphere-Ocean General Circulation Models, which are fine-tuned to smaller regions by adding area-specific information.

California models have taken some of IPCCs report estimates to propose potential impact scenarios to California's population. Key issues for the San Francisco Bay Area include: raising sea level, temperature changes and its consequent impact on energy demands, pests, agriculture, precipitation, and extreme climatic events. These issues are discussed in detail in the 2009 California Climate Adaptation Strategy Report (California Natural Resources Agency 2009).

The Climate Scenarios

Climate change simulation and adaptation/mitigation strategies are based on several proposed scenarios of the world's trajectory of population and energy trends developed by the IPCC (2000).[3] The following IPCC scenarios are used broadly from local governments to national agencies for climate change consequences specific to each area.

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more-efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system.

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[3] The summary of the A1, A2, B1 and B2 storylines have been taking directly from Figure 1 of the Emission Scenarios Special Report's Summary for Policymakers.

The three A1 groups are distinguished by their technological emphasis: fossil-fuel intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per-capita economic growth and technological change are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

California Climate Change Scenarios and Models

Climate change models for the California Climate Adaptation Strategy were developed by Cayan et al. (2009) and are described in their report for the California Climate Adaptation Strategy (California Natural Resources Agency 2009). They used A1 and B2 in their framework described above and produce projections for warming, heat waves, precipitation, sea level rise, North Pacific wind waves along the California coast, and shore zone wave runup variability. Carbon dioxide projections based on these two scenarios can be found in Figure A5 and global sea level in Figure A6. These are based on the IPCC scenarios from the Fourth Assessment Report and are described in detail in IPCC Emissions Scenarios Report (IPCC 2000).

The climate models used by Cayan et al. (2009) are "the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM); NOAA's Geophysical Fluids Dynamics Laboratory (GFDL) model, version 2.1; the NCAR Community Climate System Model (CCSM); the Max Plank Institute ECHAM5/MPI-OM; the MIROC 3.2 medium-resolution model from the Center for Climate System Research of the University of Tokyo and collaborators; and the French Centre National de Recherches Météorologiques (CNRM) models" (Cayan et al. 2009, p. 1). Furthermore, they employed a constructive analogue (CA) and bias correction and spatial downscaling (BCSD) downscaling methods for daily and monthly data respectively, which use "the coarse scale Reanalysis fields of precipitation and temperature as predictors of the corresponding fine scale fields" (Cayan et al. 2009, pg 5). Models selected for other projections (such as waves) are described in detail in their report. Within this report there are specific projections for San Francisco and the San Francisco Bay Region—see figures A7 and A8 for examples of precipitation and extreme wave height projections.

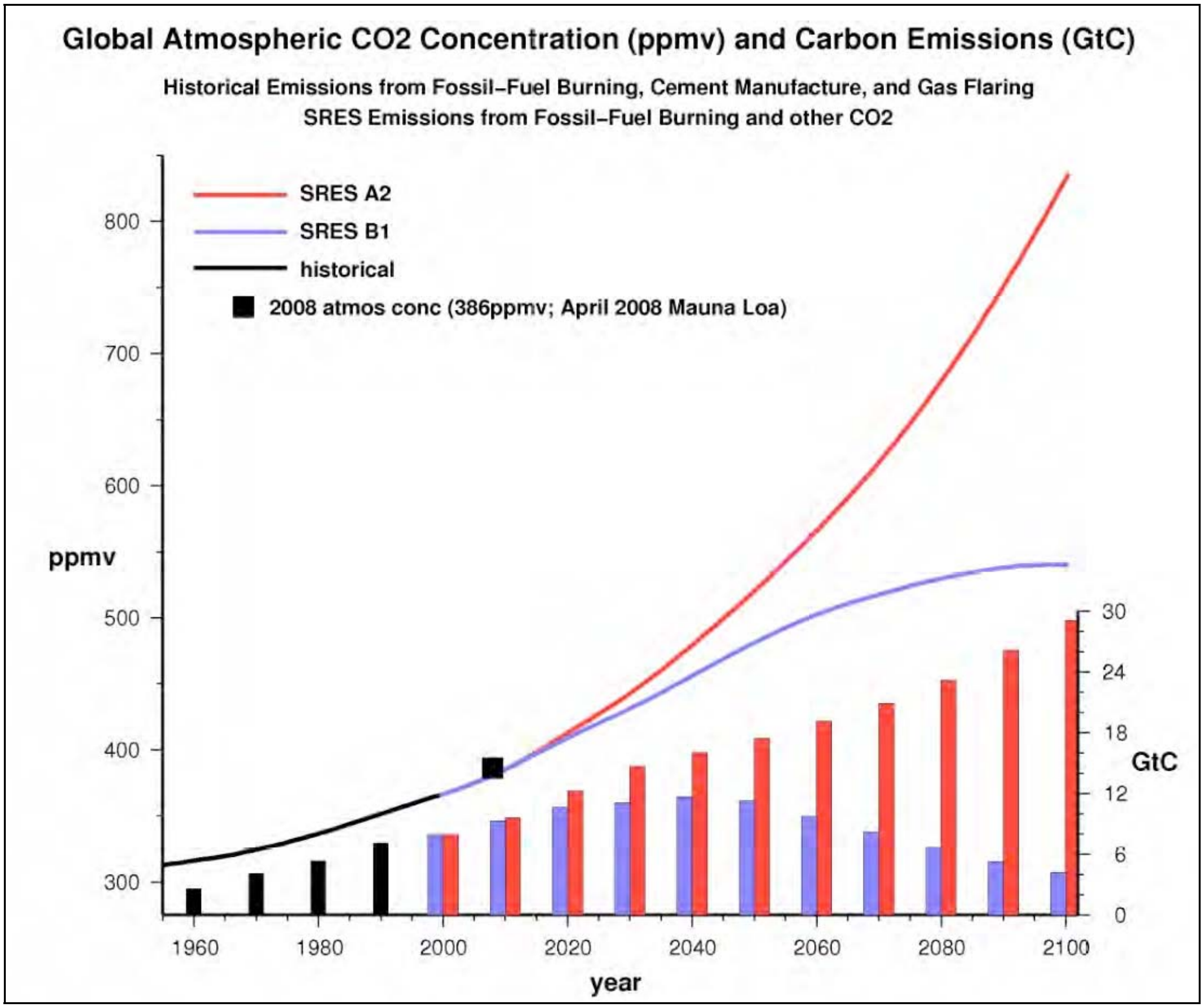

Figure A5. Global Atmospheric CO_2 Concentration (ppmv) and Carbon Emissions (GtC)

The global carbon emissions (gigatonnes of carbon, GtC) are shown by bars. The atmospheric CO_2 concentration (parts per million, volume, or ppmv) is shown by lines. The bars represent the historical period (black) and SRES B1 (blue) and SRES A2 (red) emissions scenarios. The black square represents the present day (2008) atmospheric concentration (386 ppmv).

Source: Cayan et al. 2009

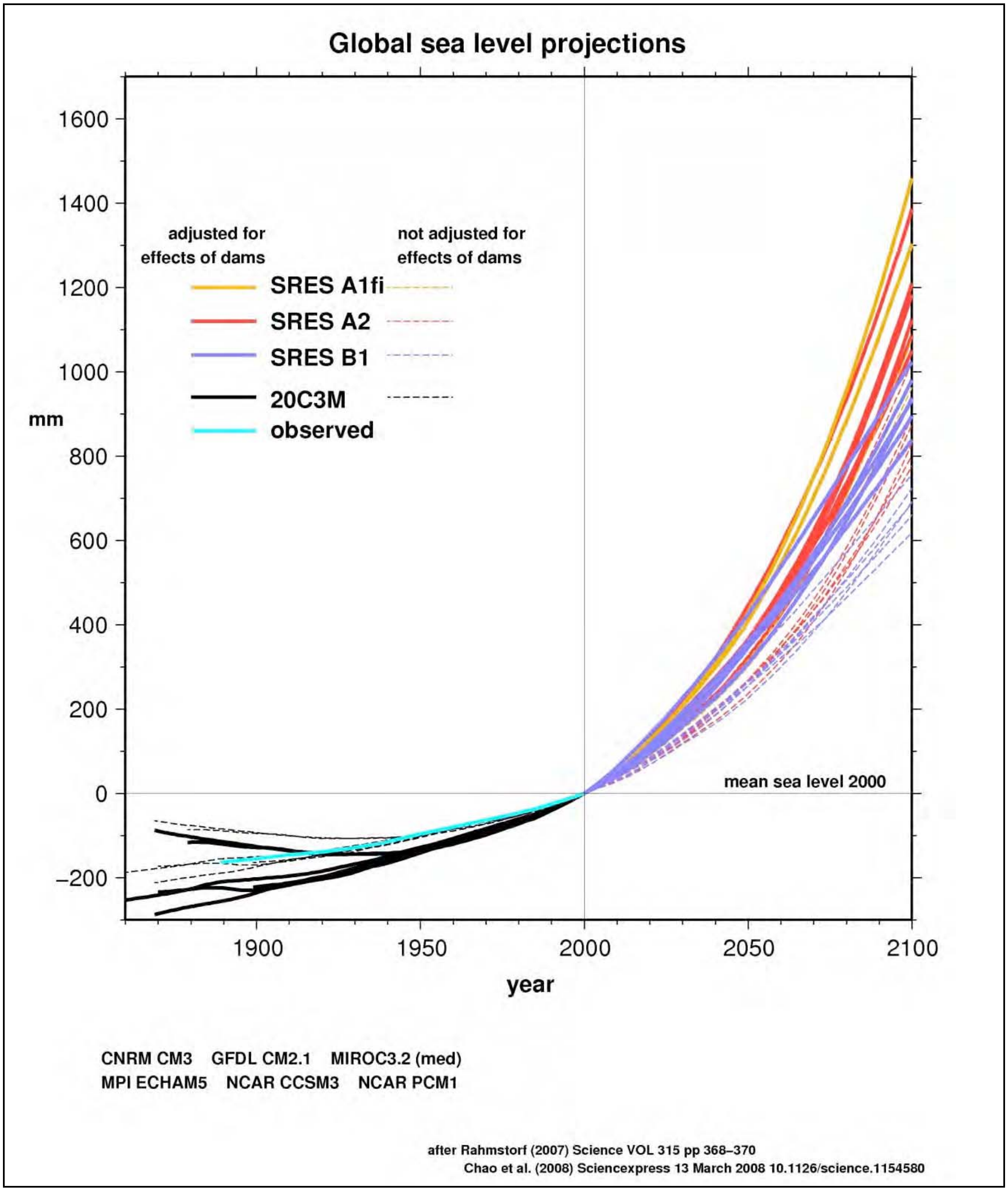

Figure A6. Global Sea Level Projections

Projected global sea level using the Rahmstorf (2007) scheme from each of the six models (set to zero at 2000). Climate change simulations for the SRES A1fi, A2, and B1 emission scenarios are shown for both the original Rahmstorf (dashed curves) and a version adjusted for the affect of reservoirs and dams (solid). Historical (black) and projected B1 simulations (blue), A2 simulations (red), A1fi (gold) are shown along with observed global sea level (aqua).

Source: Cayan et al. 2009

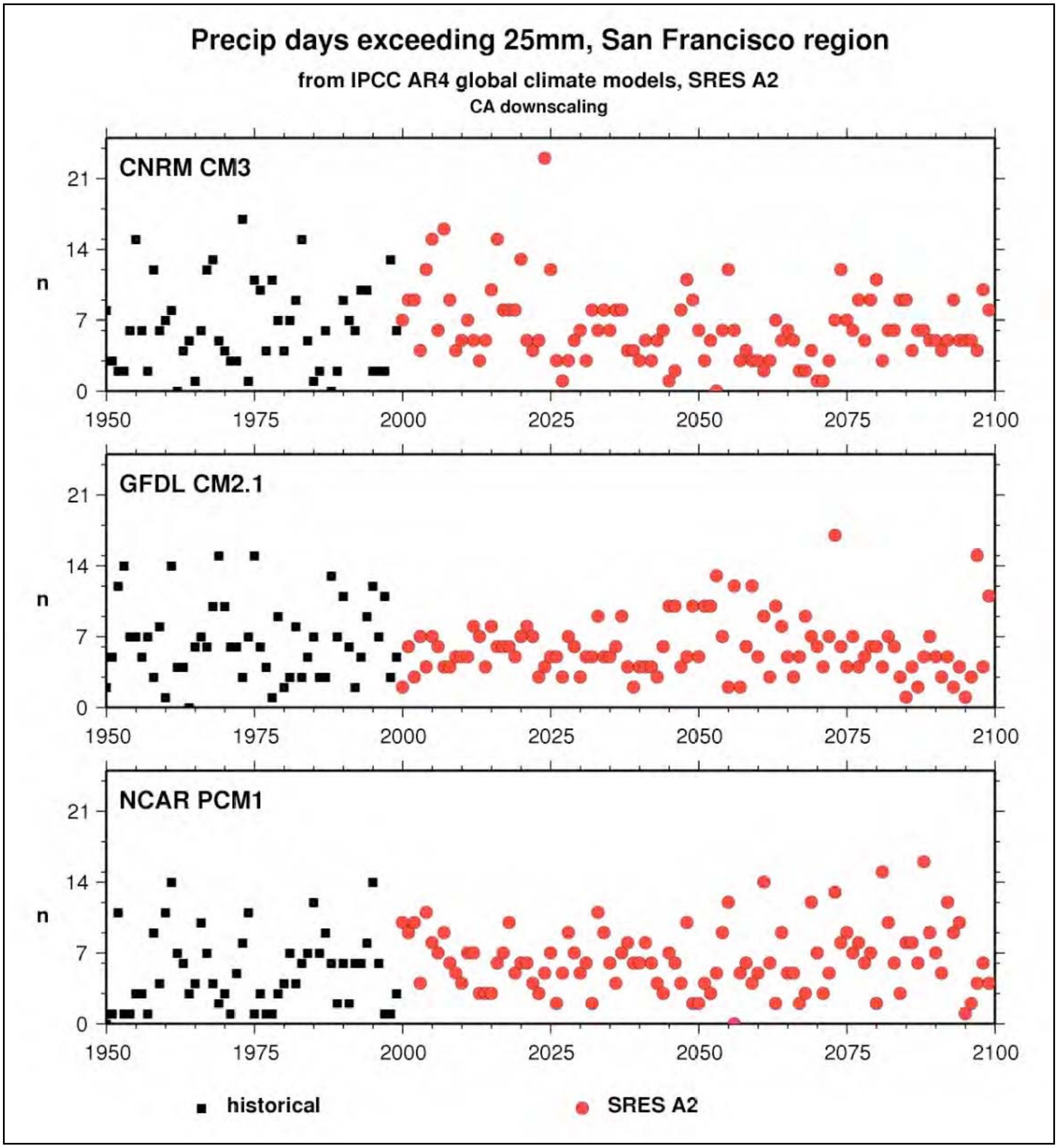

Figure A7. Precipitation Days Exceeding 25 mm, San Francisco Region

Source: Cayan et al. 2009

Number of days per year when precipitation at San Francisco equals or exceeds 25 millimeters (mm). From constructed analogues downscaling of CNRM CM3, GFDL CM2.1, and NCAR PCM1 GCMs; result from BCSD downscaling (not shown) is very similar. Historical period and A2 2000–2100 projection indicated by black and red symbols, respectively. Precipitation is taken from BCSD downscaling.

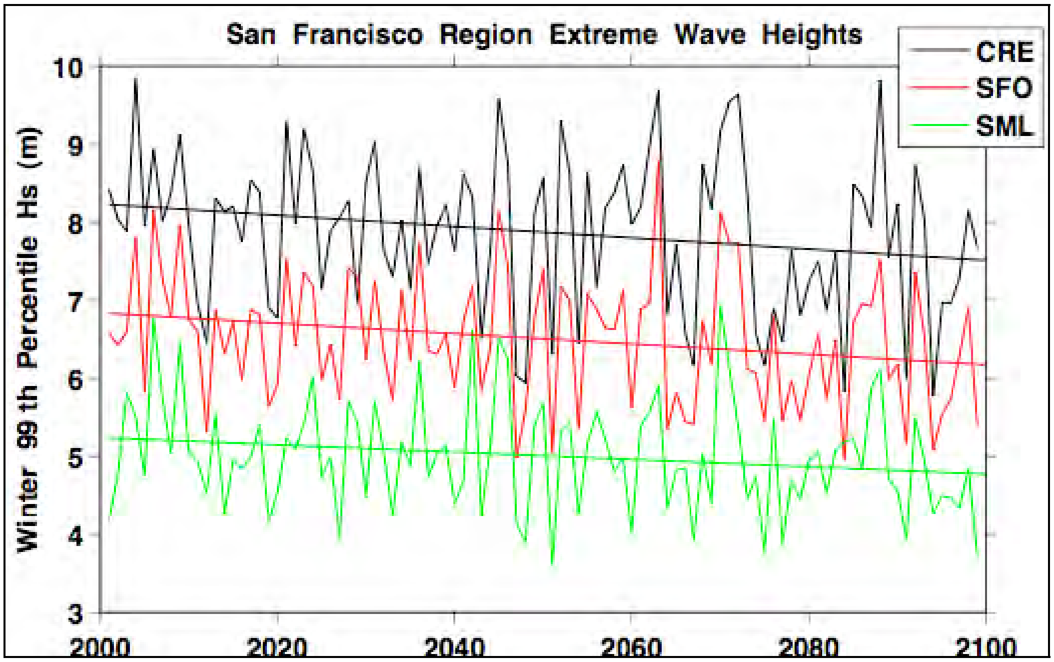

Figure A8. San Francisco Region Extreme Wave Heights

Source: Cayan et al. 2009

Winter (Nov–Mar) 99th percentiles of the WAVEWATCH III model significant wave height, *Hs*, projections forced by NCAR CCSM3 model winds. Offshore locations at northern California near Crescent City (CRE, 42oN 126oW; black), Central California near San Francisco (SFO, 38oN 124.5oW; red), and Southern California near San Miguel Island (SML, 34oN 121.5oW; green) are shown. Downward least squares trends steepen slightly going northward. These downward trends represent about a 9 percent decrease.

The Joint Policy Committee: Regional Agency Adaptation Program

For the San Francisco Bay Area, the most relevant adaptation research and policies are from the collaboration of four regional agencies with specific delegated environmental and policy responsibilities named the San Francisco Bay Joint Policy Committee (JPC). The JPC is a partnership of the Association of Bay Area Governments (ABAG), The Bay Area Air Quality Management District (Air District or BAAQMD), the Bay Conservation and Development Commission (BCDC), and the Metropolitan Transportation Commission (MTC). Together, these four agencies work on regional planning for the San Francisco Bay Area, including climate change adaptation policies and planning. These four agencies have joined forces to complement their regulatory jurisdiction over multiple facets relevant to climate change. BAAQMD has the primary regulatory responsibility over air pollution (vehicular emissions are regulated by the California Air Resources Board [CARB]); MTC has transportation planning and financial authority; ABAG offers the coordination of local governments who oversee local planning and regulations with ramifications to climate change mitigation and adaptation (the finer nuances of planning and zoning regulations are delegated to the local governments by the state); and BCDC has regulatory authority over development, albeit limited in scope to protecting the San Francisco Bay, and does not have jurisdiction over protecting the land. Unfortunately, while these are the major regional agencies, none (nor are there other agencies) have regional regulatory jurisdiction over land development to protect against the effects of climate change (such as prohibiting development in flood-prone areas, or requiring the construction of protective levees) and is left up to the local governments to regulate.

Of the Joint Policy Committee members, the San Francisco Bay Conservation and Development Commission's Climate Change Planning Program is leading much of the work on climate change adaptation in the San Francisco Bay Region. BCDC has the following goals:

- "identify and report on the impacts of climate change on San Francisco Bay;
- identify strategies for adapting to climate change;
- develop a regional task force to inform and coordinate local governments, stakeholders, and land use planning bodies in the Bay area regarding the potential Bay-related impacts of and approaches for adapting to global climate change;
- identify the findings and policies in the San Francisco Bay Plan pertaining to climate change, such as the findings and policies on sea level rise, and update other relevant Bay Plan policies to incorporate new information about the impacts of climate change" (SFBCDC 2007a).

To accomplish the goals of the Climate Change Planning Program, BCDC is undertaking the following programs (SFBCDC 2007a):

Proposed Climate Change Bay Plan Amendment – "[…] the plan should be a vision for resilient communities and adaptable natural areas around a dynamic and changing Bay that will have different sea level elevations, salinity levels, species and chemistry than the Bay has today" (SFBCDC 2008). The Commission recommends adding to the Bay Plan:
"(1) Incorporating sea level rise scenarios and using them in the permitting process;
(2) Developing a long-term strategy to address sea level rise and storm activity […]; (3) Working with the Joint Policy Committee (JPC) and other agencies to integrate regional mitigation and adaptation strategies and adaptation responses […]; (4) Providing recommendations and requirements to guide planning and permitting of development in areas vulnerable to sea level rise; and (5) Including policies that promote wetland protection, creation, enhancement and migration" (SFBCDC 2010).

Planning for Climate Change: Resources for Bay Area Local Government – This is a comprehensive list of links of resources (over 100 documents and websites) for local governments on climate change and include information the following categories: (1) climate change science and impacts; (2) adaptation planning principles and process; (3) tools, data, sources and example adaptation actions; (4) engaging communities and decision-makers; (5) example adaptation plans; and (6) state and regional adaptation planning efforts (SFBCDC 2007b).

Mapping Areas Vulnerable to Sea Level Rise – Contains detailed PDF areal imagery of the San Francisco Bay Area with overlaid sea level rise scenario impacts for each sub-region. See Figure A9 for an example.

Figure A9. 16-Inch Sea Level Rise By Mid-Century San Francisco Bay Area

Source: SFBCDC 2007c

Delta Alliance Partnership – An alliance of BCDC and a consortium of Dutch researchers who conducted a joint study on the impact of sea level rise on the San Francisco Bay. The study results are presented as the report titled "San Francisco Bay: Preparing for the next level."

Rising Tides Design Competition – BCDC hosted an open international design competition for ideas responding to sea level rise in San Francisco Bay and beyond.

Federal Agencies – In addition to the regional agencies mentioned above, "[i]n the Bay Area, five federal agencies are actively involved in shoreline adaptation: the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), the United States Army Corps of Engineers (Corps), and the Environmental Protection Agency (EPA)" (SFBCDC 2009).

San Francisco Bay Area Projections and Adaptation

Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline by BCDC (SFBCDC 2009) is the most relevant climate change adaptation plan to the San Francisco Bay Region. Additionally, the Pacific Institute's *The Impact of Sea-Level Rise on the California Coast,* which studies 1,100 miles of the Pacific Coast from Oregon to Mexico, includes a detailed section on the San Francisco Bay Shoreline (Pacific Institute 2009). Both of these reports use projections from both IPCC's Fourth Report and Cayan et al. (2009) described above. Using these projections, the report uses geographic information systems (GIS) methods to determine the effect of sea level rise of the San Francisco Bay on the San Francisco Bay Shoreline. This report makes use of the "Mapping Areas Vulnerable to Sea Level Rise" project of BCDC (Figure A9) described above to determine the extent of the affected region. It discusses in detail:

1. The shoreline environment
   - Residential Land Use (Low-income Residences and Schools and Emergency Services)
   - Commercial and Industrial Lane Use (Airports, Ports, and Water-Related Industry)
   - Public Health Impacts of Climate Change
   - Other Shoreline Land Uses, Infrastructure and Institutions (Wastewater Treatment Facilities, Flood Control Channels, Contaminated Lands, and Pipelines and Transmission Lines)
   - The Regional Transportation Network (Major Roadways and Highways and Rail Network)
   - Waterfront Parks and Beaches
2. The San Francisco Bay Ecosystem
   - Sea Level Rise in the Bay Ecosystem (Constraints to Wetland Adaptation and Salinity Change in Tidal and Subtidal Habitats)
   - Other Water Quality Impacts

- Invasive Species
- Threat of Extinction
- Shoreline Protection Impacts (Ecological Consequences of a Tidal Barrage)
- Watershed Land Use
- Restoration and Adaptive Management

The Pacific Institute's report also provides multiple sea-level rise scenarios including erosion risk estimates, and discusses the resources threatened by sea-level rise, including people, the built environment, natural resources, and infrastructure costs. Additionally, the report discusses environmental justice concerns and the association between demographics and vulnerability factors. Notably, their vulnerable populations map shows the San Francisco Bay Region as having the most people at risk (see Figure A10).

Resources for California

The most comprehensive list of all reports (local to global) with relevant to California may be found at the NOAA Collaboration Website on Climate Adaptation (NOAA 2010) and the link above from BCDC (SFBCDC 2007b). Additionally, California climate change adaptation is described in detail at the California Climate Change Portal (http://www.climatechange.ca.gov/). A summary of the 2009 California Climate Change Strategy Report from the portal is found below.

California Climate Adaptation Strategy

The 2009 California Climate Adaptation Strategy Report examines the impacts, risks, and strategies of (1) increased temperatures and extreme weather events (such as extreme heat events, fewer freezing spells, reduction of chill hours, changes in air quality, invasive species, changes to community composition and interactions, ecosystems services); (2) precipitation changes and extreme events (including floods, droughts, wildfires, and changes in stream flow); and (3) sea-level rise (infectious diseases, vector-borne diseases, water- and food-borne diseases, the food supply, coastal flooding and permanent inundation, wetland loss and habitat degradation, increased coastal erosion, salt water intrusion and ocean acidification) by sector involved in climate change.

The seven sectors are (1) Public Health (led by the Department of Public Health with assistance from the California Air Resources Board); (2) Biodiversity and Habitat (led by the Department of Parks and Recreation and the Department of Fish and Game); (3) Ocean and Coastal Resources (led by the Ocean Protection Council); (4) Water Management (led by the Department of Water Resources; (5) Agriculture (Led by the Department of Food and Agriculture and the Department of Conservation); (6) Forestry (led by the Department of Forestry and Fire Protection and the Board of Forestry); and (7) Transportation and Energy Infrastructure (led by the Department of Transportation and the California Energy Commission).

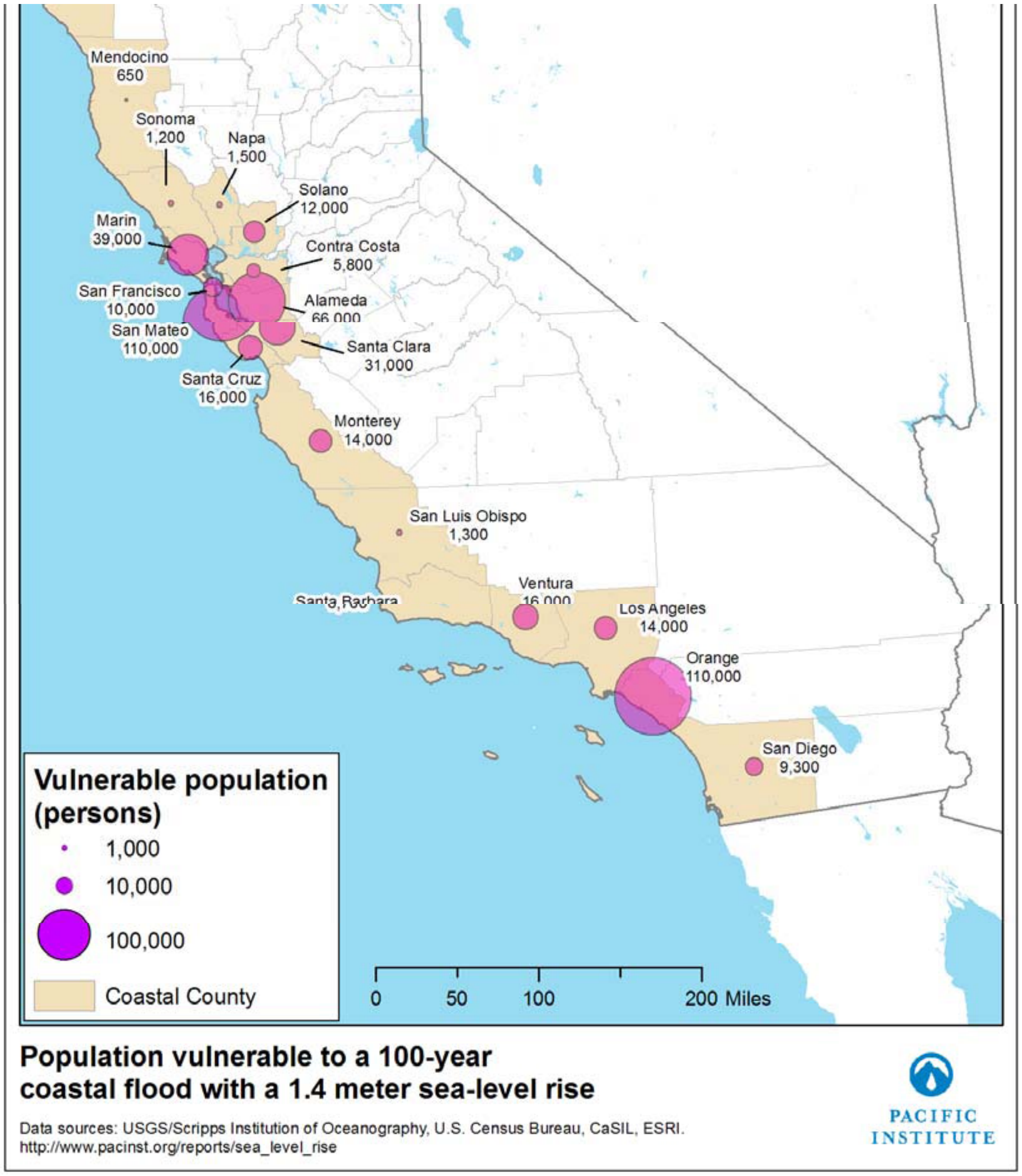

Figure A10. Population Vulnerable to a 100-yYear Coastal Flood with a 1.4 m Sea-Level Rise, by County

Source: Pacific Institute 2009, p. 41

Key Recommendations from the 2009 California Climate Adaptation Strategy

The following 12 key recommendations are from the California Adaptation Strategy, pages 7–9. (California Natural Resources Agency 2009).

1. A Climate Adaptation Advisory Panel (CAAP) will be appointed to assess the greatest risks to California from climate change and recommend strategies to reduce those risks […].
2. California must change its water management and uses […].
3. Consider project alternatives that avoid significant new development in areas that cannot be adequately protected (planning, permitting, development, and building) from flooding, wildfire, and erosion due to climate change.
4. All state agencies responsible for the management and regulation of public health, infrastructure, or habitat subject to significant climate change should prepare as appropriate agency-specific adaptation plans, guidance, or criteria […].
5. To the extent required by CEQA Guidelines Section 15126.2, all significant state projects, including infrastructure projects, must consider the potential impacts of locating such projects in areas susceptible to hazards resulting from climate change.
6. The California Emergency Management Agency (Cal EMA) will collaborate with CNRA, the CAT, the Energy Commission, and the CAAP to assess California's vulnerability to climate change, identify impacts to state assets, and promote climate adaptation/mitigation awareness through the Hazard Mitigation Web Portal and My Hazards Website as well as other appropriate sites. The transportation sector CAWG, led by Caltrans, will specifically assess how transportation nodes are vulnerable and the type of information that will be necessary to assist response to district emergencies. Special attention will be paid to the most vulnerable communities impacted by climate change in all studies […].
7. Using existing research the state should identify key California land and aquatic habitats that could change significantly during this century due to climate change. Based on this identification, the state should develop a plan for expanding existing protected areas or altering land and water management practices to minimize adverse effects from climate change induced phenomena […].
8. The best long-term strategy to avoid increased health impacts associated with climate change is to ensure communities are healthy to build resilience to increased spread of disease and temperature increases. The California Department of Public Health will develop guidance by September 2010 for use by local health departments and other agencies to assess mitigation and adaptation strategies, which include impacts on vulnerable populations and communities and assessment of cumulative health impacts […].
9. […] communities with General Plans and Local Coastal Plans should begin, when possible, to amend their plans to assess climate change impacts, identify areas most vulnerable to

these impacts, and develop reasonable and rational risk reduction strategies using the CAS as guidance […].

10. State fire fighting agencies should begin immediately to include climate change impact information into fire program planning to inform future planning efforts […].
11. State agencies should meet projected population growth and increased energy demand with greater energy conservation and an increased use of renewable energy […].
12. Existing and planned climate change research can and should be used for state planning and public outreach purposes; new climate change impact research should be broadened and funded […].

Resources for the San Francisco Bay Area

- The San Francisco Bay Conservation and Development Commission
  http://www.bcdc.ca.gov/planning/climate_change/adaptation.shtml
- Berkeley Climate Action Plan
  http://www.ci.berkeley.ca.us/ContentDisplay.aspx?id=19668

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