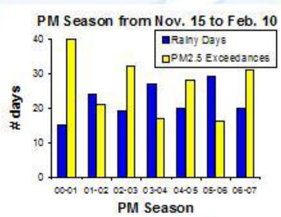
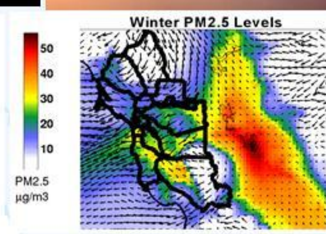
BAY AREA AIR QUALITY MANAGEMENT DISTRICT
939 Ellis Street, San Francisco, CA 94109

Research and Modeling Section Publication No. 201109-009-PM

Health Impact Analysis of Fine Particulate Matter in the San Francisco Bay Area

September, 2011





Prepared by:
Saffet Tanrikulu, Research and Modeling Manager
Cuong Tran, Senior Atmospheric Modeler
Scott Beaver, Atmospheric Modeler

Significant contributors:
Ahmet Palazoglu, UC Davis
Yiqin Jia, BAAQMD
Su-tzai Soong, BAAQMD
Phil Martien, BAAQMD
James Cordova, BAAQMD

Reviewed and approved by:
Henry Hilken, Director of Planning, Rules and Research Division

Health Impact Analysis of Fine Particulate Matter In the San Francisco Bay Area

1. Introduction

1.1 Background

Fine particulate matter ($PM_{2.5}$) is a complex mixture of suspended particles and liquid droplets in the atmosphere having aerodynamic diameters of 2.5 µm or less. An individual particle typically begins as a core or nucleus of carbonaceous material, often containing trace metals. These *primary* (directly emitted) particles usually originate from incomplete combustion of fossil fuels or biomass. Layers of organic and inorganic compounds are then deposited onto particles while they coalesce, causing the particles to grow in size. The deposited layers include *secondary* material that is not emitted directly. Secondary components instead form through chemical reactions of precursor gases released from combustion, agriculture, household activities, industry, vegetation, and other sources. As particles grow larger, gravity eventually causes them to settle onto surfaces. Most naturally emitted dust particles have diameters too large to be classified as $PM_{2.5}$.

Numerous studies have demonstrated $PM_{2.5}$ to be deleterious to human health. Major human health outcomes resulting from $PM_{2.5}$ exposure include aggravation of asthma, bronchitis, and other respiratory problems, leading to increased hospital admissions; cardiovascular symptoms, including chronic hardening of the arteries and acute triggering of heart attacks; and decreased life expectancy, potentially on the order of years. Smaller particles have increasingly more severe impacts on human health than larger particles. This occurs in part because smaller particles are able to penetrate more deeply into the human body.

The United States Environmental Protection Agency (US EPA) has developed a computer program, named the Environmental Benefits Mapping and Analysis Program (BenMAP), to estimate health impacts associated with changes in ambient levels of pollutants. Staff of the Research and Modeling Section of the Bay Area Air Quality Management District (BAAQMD) applied this program to estimate the health impacts of $PM_{2.5}$ on Bay Area residents.

In this application, the health impacts were estimated for two scenarios. The first scenario estimated the health impacts of reducing the 2010 Bay Area $PM_{2.5}$ levels to an assumed natural background level. This scenario allowed an estimate of the total public health burden of $PM_{2.5}$ over the Bay Area. The second scenario estimated the health impacts of reducing the 2010 Bay Area $PM_{2.5}$ levels by hypothetical increments of 1 $\mu g/m^3$ uniformly over the Bay Area. The incremental benefits of $PM_{2.5}$ exposure reduction were estimated down to a moderate $PM_{2.5}$ level. These increments reflected potential benefits associated with a range of emissions reduction scenarios that may be feasible over the short to medium term.

This report summarizes the regulatory history of $PM_{2.5}$, ongoing District research efforts, a summary of the BenMAP program, a description of input data preparation and BenMAP application over the Bay Area, and research results. The overall goal of this study was to assess the potential economic and health benefits of reducing Bay Area $PM_{2.5}$ levels below current levels.

1.2 Regulatory history of $PM_{2.5}$

Regulation of airborne particles started with total suspended particulates (TSP) in the original federal Clean Air Act of 1970. TSP is effectively a measure of particles with aerodynamic diameters of 100 µm or less. In 1987, TSP was replaced by PM_{10}, or particles with aerodynamic diameters of 10 µm or less. In 1997, a federal $PM_{2.5}$ standard was created in addition to the PM_{10} standard, which was retained. Since then, California has established standards for $PM_{2.5}$ and PM_{10} that are more stringent than required under federal regulations. Both the California and federal standards have been tightened as more is learned about the consequences of particulate matter exposure. This trend toward tighter PM standards is expected to continue as on-going research improves our understanding of PM health impacts.

Under federally mandated programs, the BAAQMD began measuring ambient $PM_{2.5}$ levels in 1999. $PM_{2.5}$ is a subset of PM_{10}, measured in the Bay Area since 1985. Prior to that, measurements for coefficient of haze reflected ambient levels of carbonaceous particles.

The US EPA established two National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$: a daily (24-hour) standard and an annual standard. The Bay Area currently attains the annual standard, but it was designated as a non-attainment area for the 24-hour standard based on measurements in 2006-2008. Since then, the BAAQMD has made significant progress in reducing emissions and bringing the $PM_{2.5}$ levels below the 24-hour standard.

1.3 BAAQMD research effort

A tremendous effort to advance the scientific understanding of $PM_{2.5}$ has been carried out in recent years at the federal and state levels. Because $PM_{2.5}$ is a complex mixture of individual pollutants that can vary considerably from one region to the next, research performed at the state and federal levels cannot be expected to sufficiently address the relevant intricacies of the Bay Area $PM_{2.5}$ problem. Therefore, collaborating with federal, state and local agencies, the Research and Modeling Section of the District began to study the Bay Area PM problem in 2007.

Initially, analyses of ambient measurements were conducted. These analyses characterized when, where, and to what extent elevated $PM_{2.5}$ levels occurred in the Bay Area. Increasingly sophisticated statistical analyses were subsequently applied to better understand the sources of $PM_{2.5}$ and how this pollutant is affected by the prevailing weather. Although instructive, analyses of ambient measurements were insufficient to fully characterize the Bay Area $PM_{2.5}$ problem. Therefore, computer simulations were performed to characterize $PM_{2.5}$ at times and locations for which measurements were not feasible. These modeling efforts were initially based on data resulting from the California Regional Particulate Air Quality Study (CRPAQS), provided by the California Air Resources Board (ARB). Since then, BAAQMD staff and contractors contributed to significantly improve and expand upon these initial simulations. As a result, a custom computer model was utilized to explain many of the intricacies of the Bay Area $PM_{2.5}$ problem.

Ongoing BAAQMD efforts in data analysis, emissions inventory development, and computer modeling have been documented in an interim report by Tanrikulu et al. (2009).

2. Materials and methods

2.1 US EPA's BenMAP computer program

The BenMAP computer program (US EPA, 2008) was designed to estimate impacts on human health due to changes in ambient air quality and to evaluate the associated monetary value of these health effects. The program calculates the annualized benefits, in real US dollars, upon reducing pollutant exposures for a specified population.

In particular, BenMAP computes the monetary benefits of avoiding morbidity and mortality. The valuation process takes into account both the direct costs of illnesses such as actual medical costs and lost worker hours and indirect costs reflecting *willingness to pay* to avoid the pain and suffering. The direct costs alone may substantially underestimate the total value of avoiding these two outcomes. For pollutants capable of causing death, as is the case with $PM_{2.5}$, the mortality-based component tends to far outweigh the morbidity-based component. The calculations implemented by BenMAP include assessing the change in population exposure, using health impact functions to estimate the incremental change in adverse health outcomes based on the exposure difference, and evaluating the range of monetary valuations of these adverse human health outcomes.

Epidemiological data were used to develop concentration-response functions which quantify the linkages between pollutant exposures and adverse health outcomes. These functions are typically stratified by population subgroups (for example, age groups) and account for the effects associated with a specific duration of pollutant exposure. Population data and pollutant concentration data input to BenMAP must be prepared in a manner consistent with the concentration-response functions. Epidemiological data linking $PM_{2.5}$ exposure and mortality are typically stratified by age group (e.g., infants, 18 years old and over, etc.) and reflect an annual averaging period.

The BenMAP program overlays population data onto changes in ambient pollutant concentrations to calculate spatially resolved impacts associated with pollutant exposure. Pollutant concentration data were taken from gridded air quality simulations. The study described in this report was the first of its kind to use high-resolution simulated pollutant fields to evaluate $PM_{2.5}$ health impacts over the Bay Area. High resolution simulations reproduced the sharp pollutant spatial gradients that resulted in significant neighborhood-to-neighborhood differences in pollutant exposures. To ensure that the simulated pollutant levels were realistic, model performance was evaluated.

An alternative approach is to use monitoring data to estimate pollutant exposures in lieu of computer modeling. This approach requires interpolating the pollutant levels from a network of often sparsely positioned monitors to construct levels over unmonitored neighborhoods. The interpolation is problematic in practice because the sampling locations and times are biased by design. Measurements are typically made at sites distant from sources of pollution, and they may not be made continuously. Overall, modeling can better predict at the local scale how changes in emissions will impact PM concentrations, population exposure, and thus the health impacts related to PM exposure.

2.2 BenMAP inputs preparation

Air quality simulations were conducted to prepare pollutant concentration data to serve as BenMAP inputs. Annual average $PM_{2.5}$ levels were estimated as the average of the quarterly averages over four seasons (Figure 1). $PM_{2.5}$ levels were explicitly simulated for the winter season during which $PM_{2.5}$ levels were much higher than all other seasons. The winter simulations were representative of the $PM_{2.5}$ spatial distribution associated with the bulk of annual exposure. For the purposes of this study, it was assumed that the winter-season $PM_{2.5}$ spatial distribution was valid for the other seasons. The gridded winter-season $PM_{2.5}$ field was scaled uniformly across all grid cells to produce spatial distributions for the other seasons. The seasonal scaling factors were derived from ratios of monitoring data for the respective seasons. Summer $PM_{2.5}$ levels were assumed to be one-fourth of the winter levels, while spring and fall $PM_{2.5}$ levels were assumed to be one-third to one-half of the winter levels. This scaling to account for seasonality introduces uncertainty, especially for summer for which the $PM_{2.5}$ spatial distribution may differ considerably from the winter's.

$PM_{2.5}$ levels were simulated using the US EPA's Community Multiscale Air Quality (CMAQ) model computer program. Simulations were conducted using a 4-km horizontal grid size. This high-resolution modeling accounted for sharp $PM_{2.5}$ spatial gradients and took advantage of the spatial resolution of the population data. Simulations were conducted using an emissions inventory from 2005 previously developed as part of the District's Community Air Risk Evaluation program. This is the most comprehensive $PM_{2.5}$ modeling inventory developed for the Bay Area to date. Meteorological inputs to CMAQ were prepared based on the 2006-07 winter season. This winter was a representative year in terms of $PM_{2.5}$ levels and weather in the Bay Area.

Population data, including age distribution information, were taken from the 2000 US Census and projected to 2010. They were resolved at the census block level. For BenMAP use, the data were aggregated to the same 4-km resolution as the pollutant concentration data. Age distribution information was used to account for sensitive groups such as infants. Sensitive groups may benefit more from a given level of exposure reduction. Income distribution information was used to account for spatial variability in the willingness to pay to avoid exposure. Subpopulations with higher incomes tend to be willing to pay more, and they are associated with higher indirect mortality costs.

2.3 Health impacts scenarios

BenMAP estimates public health benefits based on changes in ambient air quality between *baseline* and *controlled* pollutant levels. In this study, the same baseline $PM_{2.5}$ level reflecting year 2010 was used in all BenMAP calculations. Two scenarios involving differently controlled levels were examined. For both scenarios, health benefits were estimated for the year 2010 Bay Area population.

The baseline $PM_{2.5}$ level was adjusted from the simulation output to match observed $PM_{2.5}$ levels for year 2010. For this purpose, a Bay Area "design value" for 2010 was computed in a manner consistent with US EPA attainment designation of 24-hour $PM_{2.5}$. The computed design value (98th percentile of observed $PM_{2.5}$ levels) was around 31 $\mu g/m^3$. The design value for the simulation outputs, based on the grid cells containing the monitoring locations, was around 36 $\mu g/m^3$. A scaling factor of 31/36 (about 0.86) was applied to the simulation output to yield baseline concentration fields reflecting $PM_{2.5}$ levels for 2010 (Figure 1).

The first controlled scenario explored the benefits of eliminating 90 percent of all 2005 anthropogenic emissions to bring Bay Area $PM_{2.5}$ levels to an assumed natural background level. For this scenario, emissions were not reduced by a full 100 percent to avoid unduly stressing the chemistry module of the computer model. Natural emissions were not modified. Otherwise, the simulation was conducted and outputs were processed identically to the baseline scenario.

The second controlled scenario explored the benefits of incrementally reducing $PM_{2.5}$ levels uniformly across the Bay Area. The baseline $PM_{2.5}$ spatial distribution was systematically scaled down by 1 $\mu g/m^3$ increments, uniformly for all model grid cells. We generated 11 such controlled pollutant fields, corresponding to design values ranging from 30 $\mu g/m^3$ to 20 $\mu g/m^3$. These eleven scaled control levels were used in separate BenMAP calculations as end points relative to the 2010 baseline level.

3. Results

3.1 Benefits of reducing 2010 $PM_{2.5}$ levels to a natural background level

3.1.1 Total numbers of avoided incidents by health endpoint

Table 3.1 summarizes the morbidity- and mortality-related human health impacts in terms of the change in the number of incidents of each health endpoint group per year due to reducing ambient $PM_{2.5}$ levels to an assumed natural background level. The values represent totals for all nine Bay Area counties, including all of Solano and Sonoma counties, as estimated by BenMAP. Note that not all age groups are addressed within each health endpoint group. This is because BenMAP only estimates impacts on the subpopulations associated with the available health impact functions for the particular health outcome. Therefore, information provided in Table 3.1 is constrained by the default health impact function age range.

As can be seen in the table, acute respiratory symptoms were by far the most common health effect attributed to $PM_{2.5}$. These health endpoints impacted the Bay Area adult (18 to 64 years old) population of approximately 5 million people in 2010. On average, there was approximately one-third of a restricted activity day (caused by acute respiratory symptoms) per adult per year in the Bay Area, as compared to a natural clean background scenario. It is likely that the same people experienced multiple restricted activity days throughout the year, but BenMAP can only estimate aggregate risks. The model does not track individual risks so it cannot state whether the overall risks are experienced by a small group or spread out over the adult population. Nevertheless, the large number of incidents indicated that current $PM_{2.5}$ levels have a sizeable effect on the Bay Area population.

Asthma exacerbation was also prevalent, with over 35,000 cases per year including hospital admissions, emergency room visits, and exacerbated asthma. The latter two of these asthma-related health end points impacted only the Bay Area childhood (under 18 years old) population of existing asthmatics. The percentage of affected individuals can be high in areas having both large numbers of asthmatics and elevated $PM_{2.5}$ concentrations. In addition to the pervasive impacts on the wider population, some subpopulations can experience disproportionally large impacts due to their health status as well as their locale.

The rate of premature mortality due to the 2010 $PM_{2.5}$ level was estimated to be 1,705 per year. For purposes of comparison, approximately 40,000 Bay Area residents die each year from all causes combined.

Table 3.1. Reductions in the number of incidents of various health endpoint groups.

Health Endpoint Group	Total Incidents Reduced	Age Groups Included
Mortality (all causes)	1,705	Infants, 30+
Chronic bronchitis	1,446	27+
Acute myocardial infarction (nonfatal)	1,569	18+
Hospital admissions, respiratory	477	All ages
Hospital admissions, cardiovascular	873	18+
Emergency room visits, respiratory	1,116	0-17
Acute bronchitis	2,723	8-12
Lower respiratory symptoms	35,613	7-14
Upper respiratory symptoms	29,146	9-11
Acute respiratory symptoms	1,722,345	18-64
Work loss days	294,127	18-64
Asthma exacerbation	35,363	6-18

3.1.2 Spatial distribution of key health endpoints

Figures 2-4 map the number of avoided incidents of three important health endpoint groups, respectively: asthma-related emergency room visits by children under 18, nonfatal acute myocardial infarction (heart attack), and mortality. Figures 5-7 map the same three health endpoint groups, respectively, as rates per population. Asthma-related emergency room visits are shown as rates per 10,000 children, while myocardial infarction and mortality are shown as rates per 10,000 adults.

Asthma-related health incidents were highest where the affected population density was high and local anthropogenic emissions contributed significantly, for example in West Oakland and Alameda (Figure 2). When normalized by population (Figure 5), the incidence of asthma-related emergency room visits was highest in the East Bay for Alameda, Contra Costa, and western Solano Counties, respectively. Thus West Oakland/Alameda would stand to benefit most on both absolute and normalized bases.

Incidents of myocardial infarction tended to track population density (Figure 3). Incidence rates (Figure 6), however, were relatively uniform throughout the Bay Area.

The largest mortality impacts were seen over San Francisco and West Oakland (Figure 4). The number of premature deaths per year from exposure to PM2.5 may be in excess of 100 per grid cell in certain of the 4-km grid cells in these areas. These urban areas were both densely populated and exhibited $PM_{2.5}$ concentrations that were strongly influenced by locally emitted direct $PM_{2.5}$. These areas benefited the greatest, and would be expected to benefit the fastest, when reducing anthropogenic emissions across the Bay Area. When normalized by population, however, the benefits were mostly distributed uniformly across the Bay Area (see Figure 7). Exceptions included several mortality rate hot spots outside of densely populated centers: Grizzly Bay near Vallejo, around Walnut Creek, Russell City (a community in the western area of Hayward Livermore, and Milpitas. These areas reflected locally high baseline mortality rates such as those associated with communities having proportionately more elderly residents.

3.1.3 Monetary valuations

Table 3.2 summarizes the monetary valuations associated with the health endpoint groups, aggregated at the county level and totaled for the Bay Area. Valuations are shown separately as sums for the morbidity- and mortality-related health endpoint groups listed in Table 3.1. The mortality-related valuation is typically an order of magnitude larger than the morbidity-related valuation for a given County. Mortality is the dominant driver for the overall monetary valuation of the health impacts of $PM_{2.5}$.

Table 3.2. Monetary valuations associated with health impacts estimated for 2010 PM levels (relative to a clean baseline).

County	Mortality Valuation (million)	Morbidity Valuation (million)	Total (million)	Mortality Valuation per Capita
Alameda	$2,715	$201	$2,916	$1,751
Contra Costa	$2,206	$154	$2,360	$2,050
Marin	$410	$25	$435	$1,618
Napa	$216	$11	$227	$1,515
San Francisco	$1,893	$119	$2,012	$2,314
San Mateo	$1,000	$69	$1,069	$1,357
Santa Clara	$2,728	$237	$2,965	$1,485
Solano	$614	$44	$658	$1,392
Sonoma	$806	$50	$856	$1,626
Grand Total	**$12,588**	**$910**	**$13,498**	

Note: Values are given in 2006 dollars.

The total benefit of reducing current $PM_{2.5}$ concentrations to a clean background level was estimated as $13.5 billion. Over 93 percent of the total was the mortality-related component. Santa Clara and Alameda counties show similar benefits, together accounting for 44 percent of the total. They are followed by Contra Costa ($2.4 billion) and San Francisco ($2 billion) Counties. Napa County has the smallest benefit, approximately $228 million.

Valuations on a per capita basis varied significantly, ranging from $1,357 for San Mateo County to nearly twice as high at $2,314 for San Francisco County. These findings were influenced by a combination of factors: simulated $PM_{2.5}$ changes in response to emission reductions, population density, population proximity to areas impacted by local emissions, baseline incidence rates for each health endpoint, and age demographics.

3.2 Impacts of incremental reductions in 2010 $PM_{2.5}$ levels

Figures 8 and 9 show the response of the mortality- and morbidity-related valuations, respectively, to incremental reductions in the ambient $PM_{2.5}$ level. The annual benefits for each 1 $\mu g/m^3$ reduction in $PM_{2.5}$ levels were approximately $500 million and $37 million for the mortality- and morbidity-related health endpoints, respectively. For the range of concentration differences explored in this study, both the mortality- and morbidity-related valuations were linear with respect to changes in the $PM_{2.5}$ level. Changes in the number of incidents of each health endpoint group per 1 $\mu g/m^3$ reduction in $PM_{2.5}$ levels are shown in Table 3.3.

Table 3.3. Benefits of incremental (per 1 μg/m^3) reductions in ambient PM2.5.

Health Endpoint Group	Total Incidents Reduced
Mortality (all causes)	66
Chronic bronchitis	61
Acute myocardial infarction (nonfatal)	71
Hospital admissions, respiratory	19
Hospital admissions, cardiovascular	29
Emergency room visits, respiratory	46
Acute bronchitis	117
Lower respiratory symptoms	1,493
Upper respiratory symptoms	1,126
Acute respiratory symptoms	68,348
Work loss days	11,530
Asthma exacerbation	1,362

Note: Totals include all portions of Solano and Sonoma counties.

4. Discussion

Results obtained in this study were compared to estimates from other sources. One such source is the 2010 Clean Air Plan (CAP) adopted by the District in September, 2010. The health burden created by $PM_{2.5}$ in the Bay Area was estimated to total about 2,700 premature deaths for 2008. This compares well with this study's finding of 1,705 deaths for 2010. The main difference arises from estimates of the difference in current and background $PM_{2.5}$ levels. The estimated total public health burden ($20 billion per year) based on the CAP methodology also compares reasonably well against the benefits estimated in this study ($13.5 billion per year) in 2006 dollars.

Results from this study were also compared to recent work done by the California Air Resources Board (ARB, 2010). ARB staff essentially applied the same version of BenMAP and estimated the benefits associated with reducing 2006-2008 $PM_{2.5}$ levels to 5.8 μg/m^3. They found that total avoided premature mortalities for the Bay Area would be between 520 and 1,100, with a mean of 810. While the estimates among the three studies are in the same vicinity, they do represent a range of values, with the CAP being at the high end, ARB's estimate at the low end, and this study being in between.

One key difference in methodology between this work and the other two studies is the use of an air quality simulation to produce highly spatially resolved concentration fields. While the use of observed $PM_{2.5}$ data is desirable, it presents two limitations for BenMAP analyses. First, spatial interpolation is necessary where no observations are available. Because monitoring sites are chosen to capture the higher pollutant levels, this may introduce bias into interpolated concentration fields. Second, and perhaps more importantly, BenMAP requires a set of both base and controlled concentration fields. Even if the observations yield a representative baseline field, the controlled field is typically developed by "rolling back" the base case;

therefore, the spatial distribution in the controlled field may not reflect the pattern of emission reductions. This has important implications in BenMAP since the proximity of affected populations to concentration changes significantly impacts the results. In this study, the simulation results were tied to the monitoring data by scaling the simulated concentration fields to match the design value calculated from the monitoring data for year 2010.

Results of this study were also compared against spatial patterns of health endpoint groups impacts tabulated as part as the BAAQMD CARE Program (BAAQMD, 2006). Numbers of actual asthma-related hospitalizations were compiled by zip code. These raw hospitalization data were age-adjusted for children 14 years old and younger using 1-year increments, and mapped spatially over the Bay Area using 1-km horizontal grid resolution (Figure 10). The CARE study found that the northwest quadrant of Alameda County had the highest asthma-related hospitalization rates for children under the age of 14. Results of the CARE program were not directly comparable with this current study due to differences in the age-adjustment and spatial mapping processes. The CARE results, were, however spatially consistent with the age-adjusted spatial distribution of asthma-related emergency room visits (Figure 5). Together, these studies suggest that this hotspot area is the most sensitive to asthmatic triggers and stands to reap the largest asthma-related benefits from reducing the ambient $PM_{2.5}$ level.

5. Conclusions

This study estimated the health and associated monetary benefits of reducing ambient $PM_{2.5}$ levels in the Bay Area. We found that current pollutant levels contribute significant negative health impacts to the Bay Area's population and that reducing $PM_{2.5}$ can result in half a billion dollars in benefits for every reduction of 1 $\mu g/m^3$. San Francisco and Oakland experienced the largest health impacts from $PM_{2.5}$.On a per capita basis, however, the health impacts are fairly uniform with the exception of asthma-related hospitalizations, which affect children in the East Bay disproportionately.

One limitation of the current study is the assumption that the winter season spatial distribution of $PM_{2.5}$ concentrations is applicable to other seasons. This can be a poor assumption because some emission sources are more active in one season than others and the spatial distributions of emissions vary by source. For instance, the absence of wood smoke emissions during summer can be accounted for more accurately than has been assumed in this study. Another refinement to this work is the use of updated data as they become available. One important input to BenMAP is population data. For this work, population data from the 2000 US Census were projected to 2010 levels. This extrapolation may have misrepresented the spatial distribution of population growth within the Bay Area over the past decade. These refinements and others are planned for future updates to this work.

6. References

(ARB, 2010). "Estimate of Premature Deaths Associated with Fine Particle Pollution (PM2.5) in California Using a U.S. Environmental Protection Agency Methodology," [Available from the California Air Resources Board]. August, 2010.

(BAAQMD, 2006). “Community Air Risk Evaluation Program: Phase I Findings and Policy Recommendations Related to Toxic Air Contaminants in the San Francisco Bay Area,” [Available from the Bay Area Air Quality Management District]. September, 2006.

(BAAQMD, 2010). “2010 Clean Air Plan,“ [Available at http://www.baaqmd.gov/Divisions/Planning-and-Research/Plans/Clean-Air-Plans.aspx]. September, 2010.

(Tanrikulu et al., 2009). “Fine particulate Matter Data Analysis and Modeling in the Bay Area,” [Available from the Bay Area Air Quality Management District]. October, 2009.

(US EPA, 2008). “Environmental Benefits Mapping and Analysis Program,” [Available from the US Environmental Protection Agency]. September, 2008.

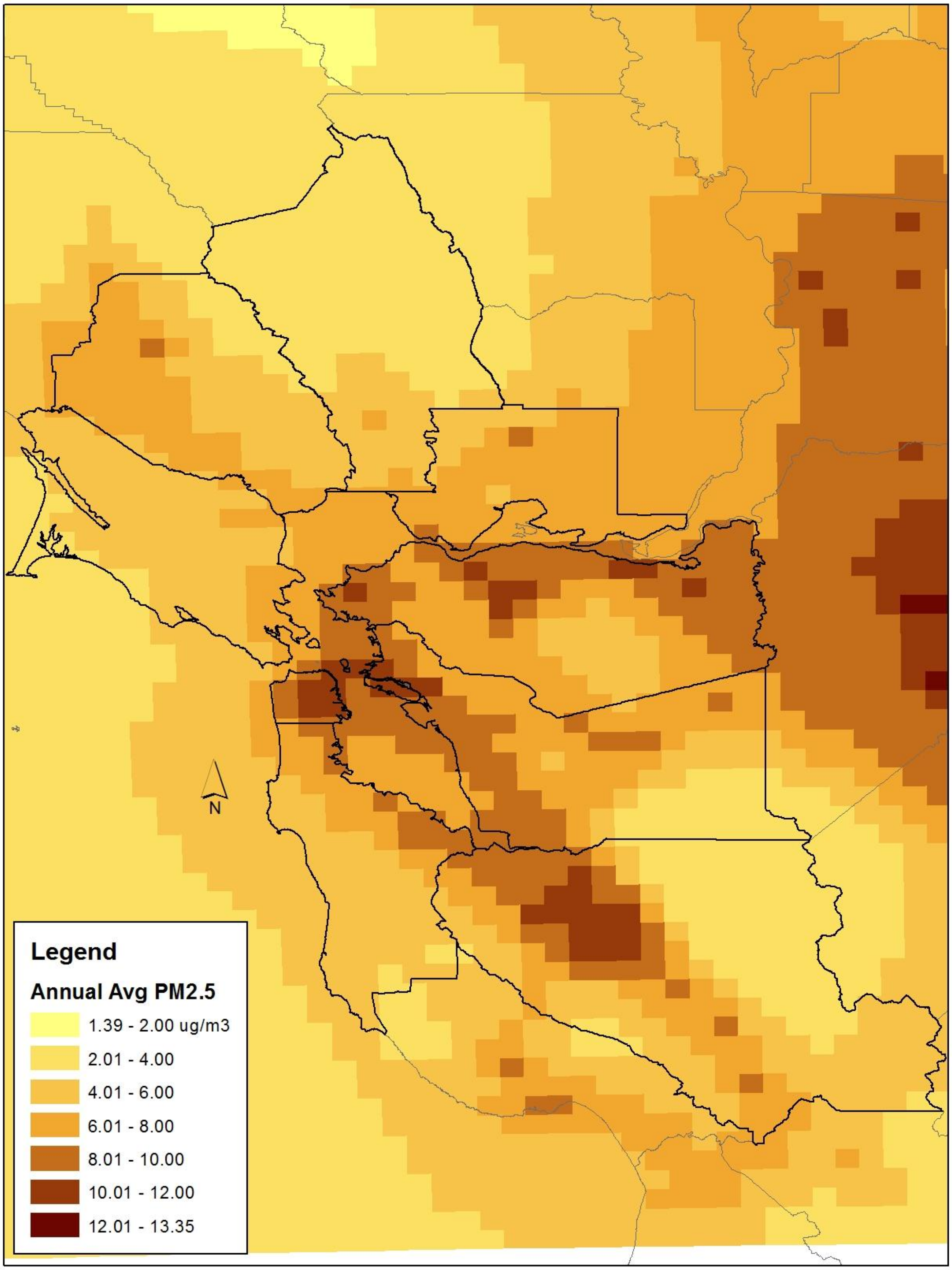


Figure 1. Baseline annual average $PM_{2.5}$ concentration field.

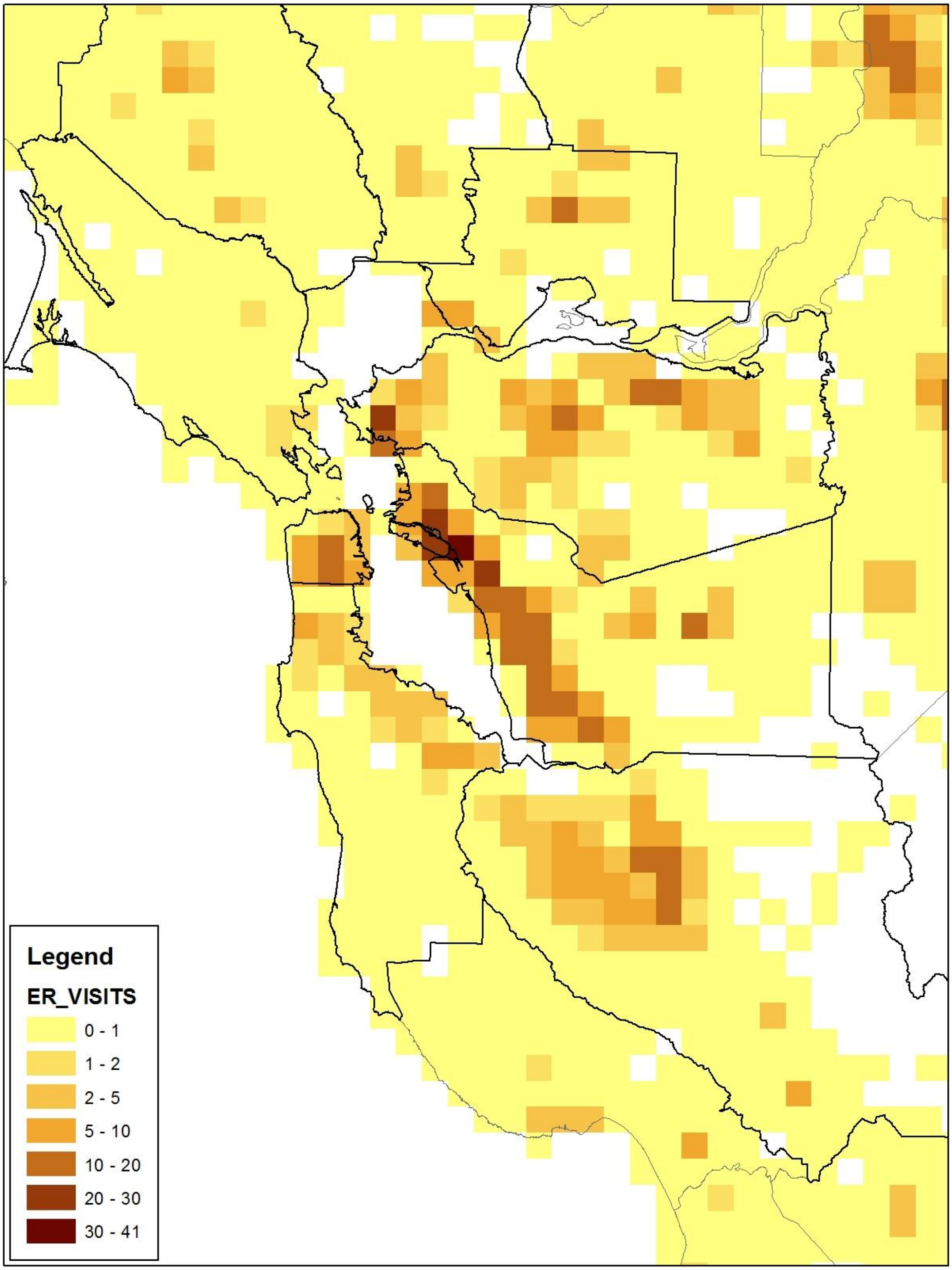


Figure 2. Reductions of emergency room visits for asthma-related symptoms for children under 18.

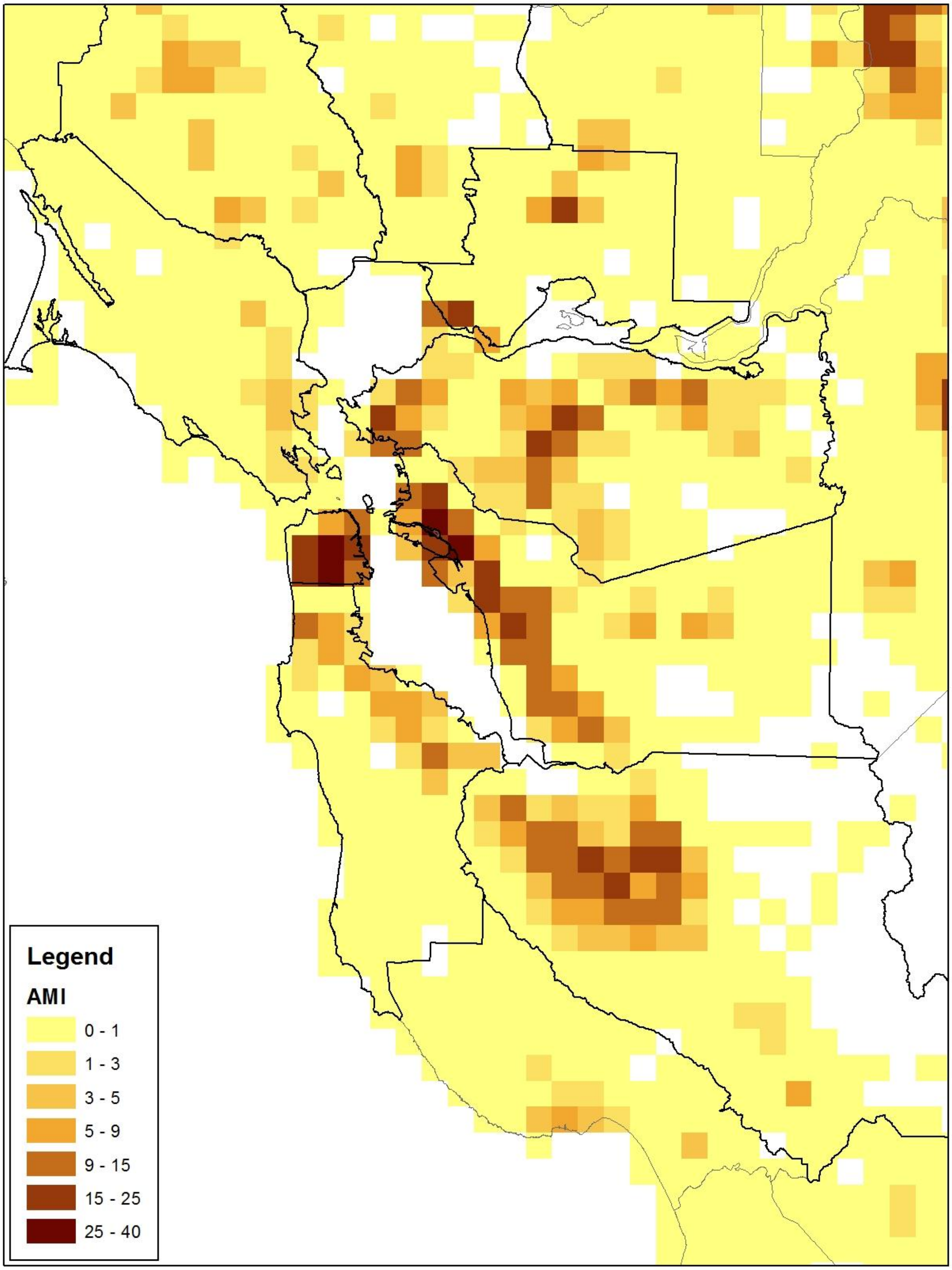


Figure 3. Reductions of acute myocardial infarctions.

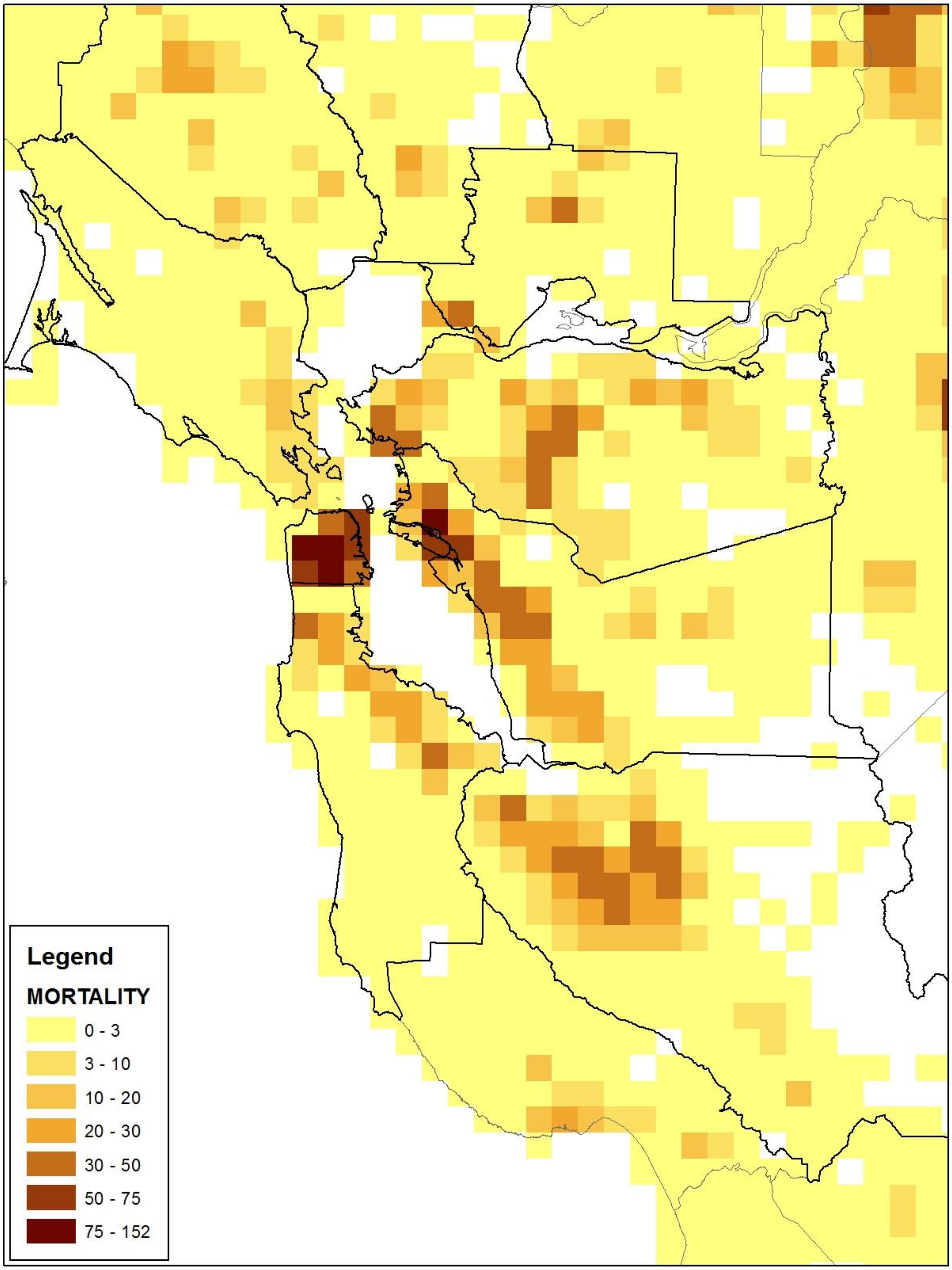


Figure 4. Reductions of mortality incidence.

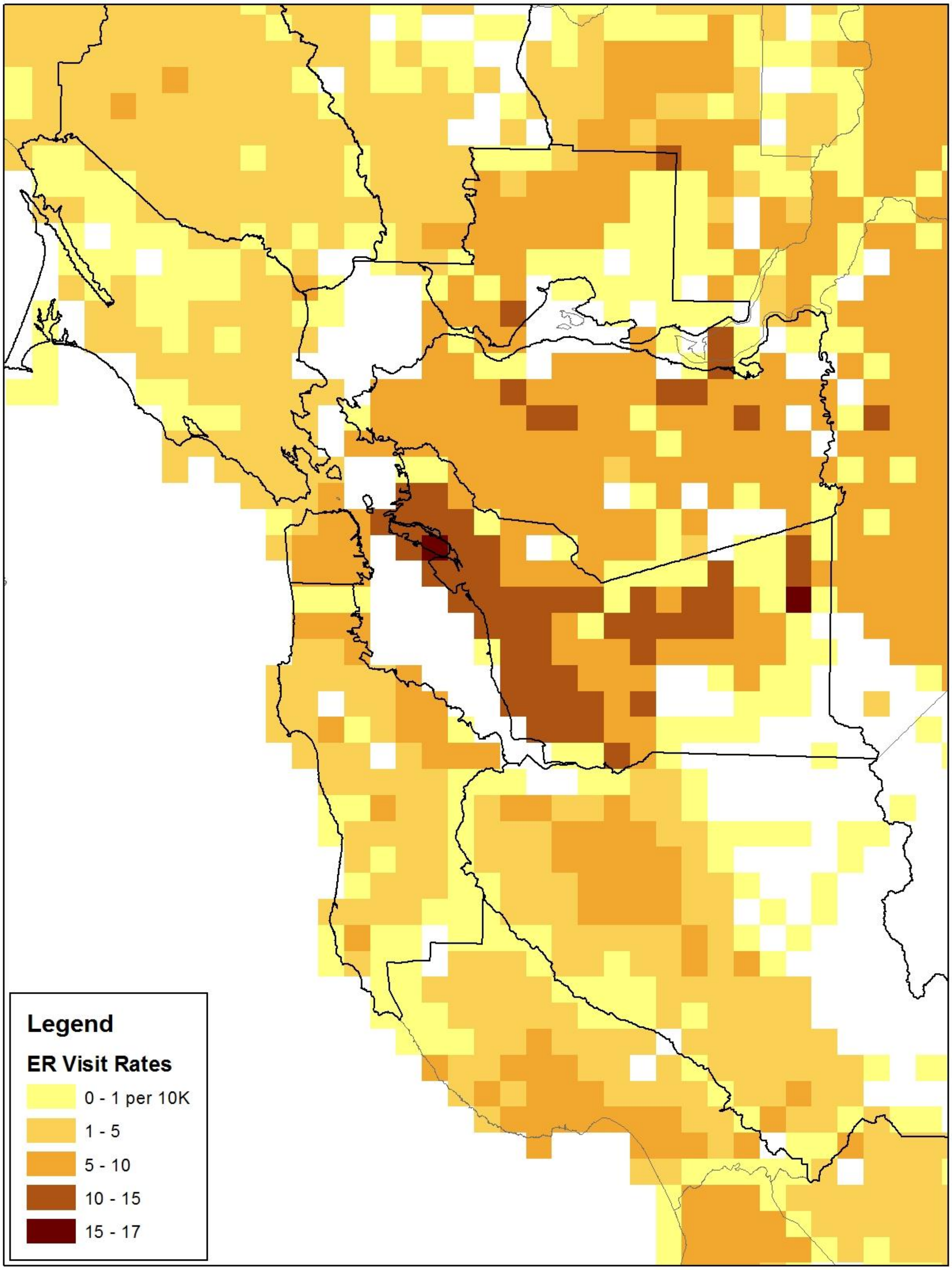


Figure 5. Reductions of asthma-related emergency room visits per 10K population of children under 18.

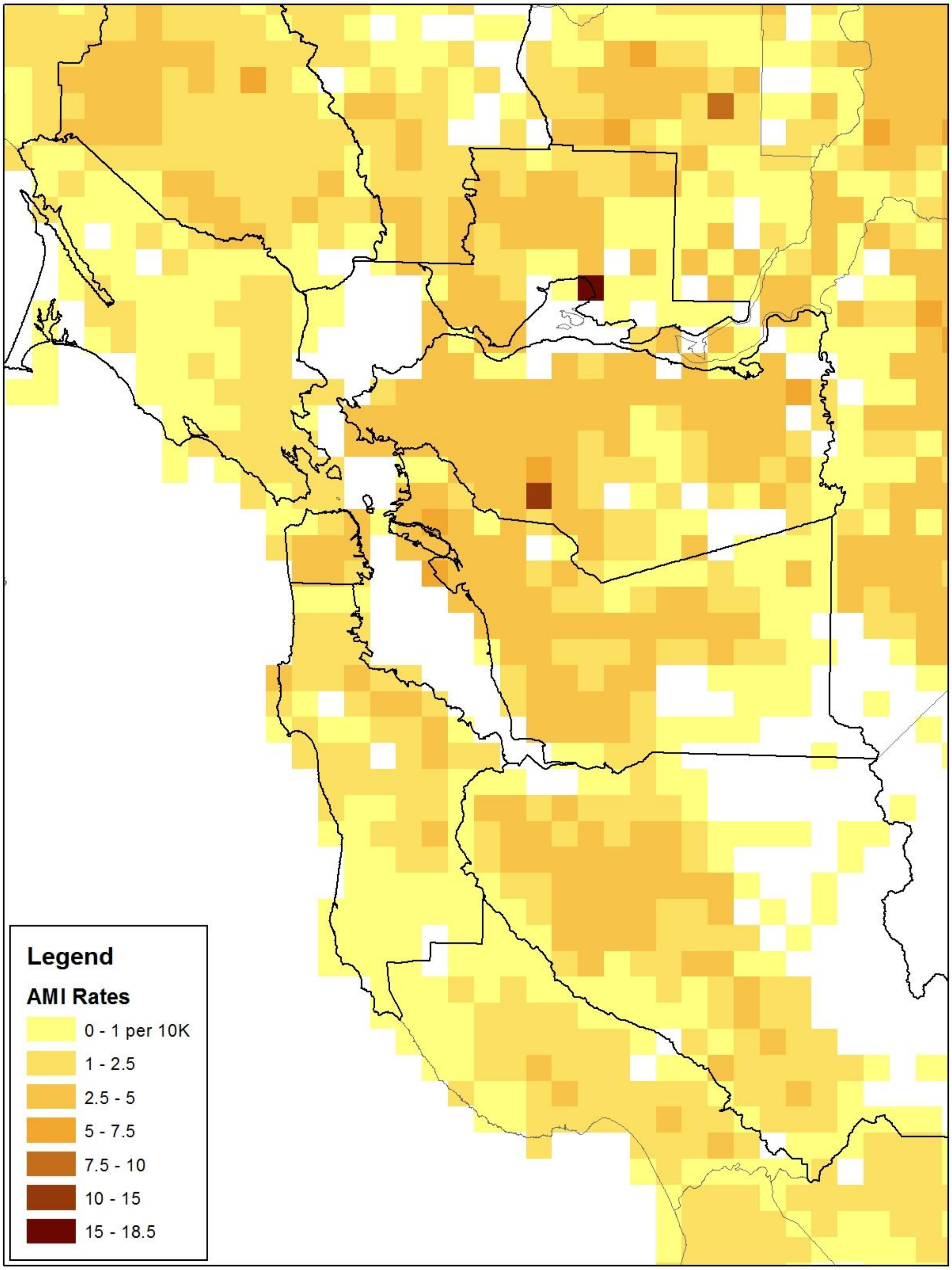


Figure 6. Reductions of acute myocardial infarction rates (incidents per 10K population).

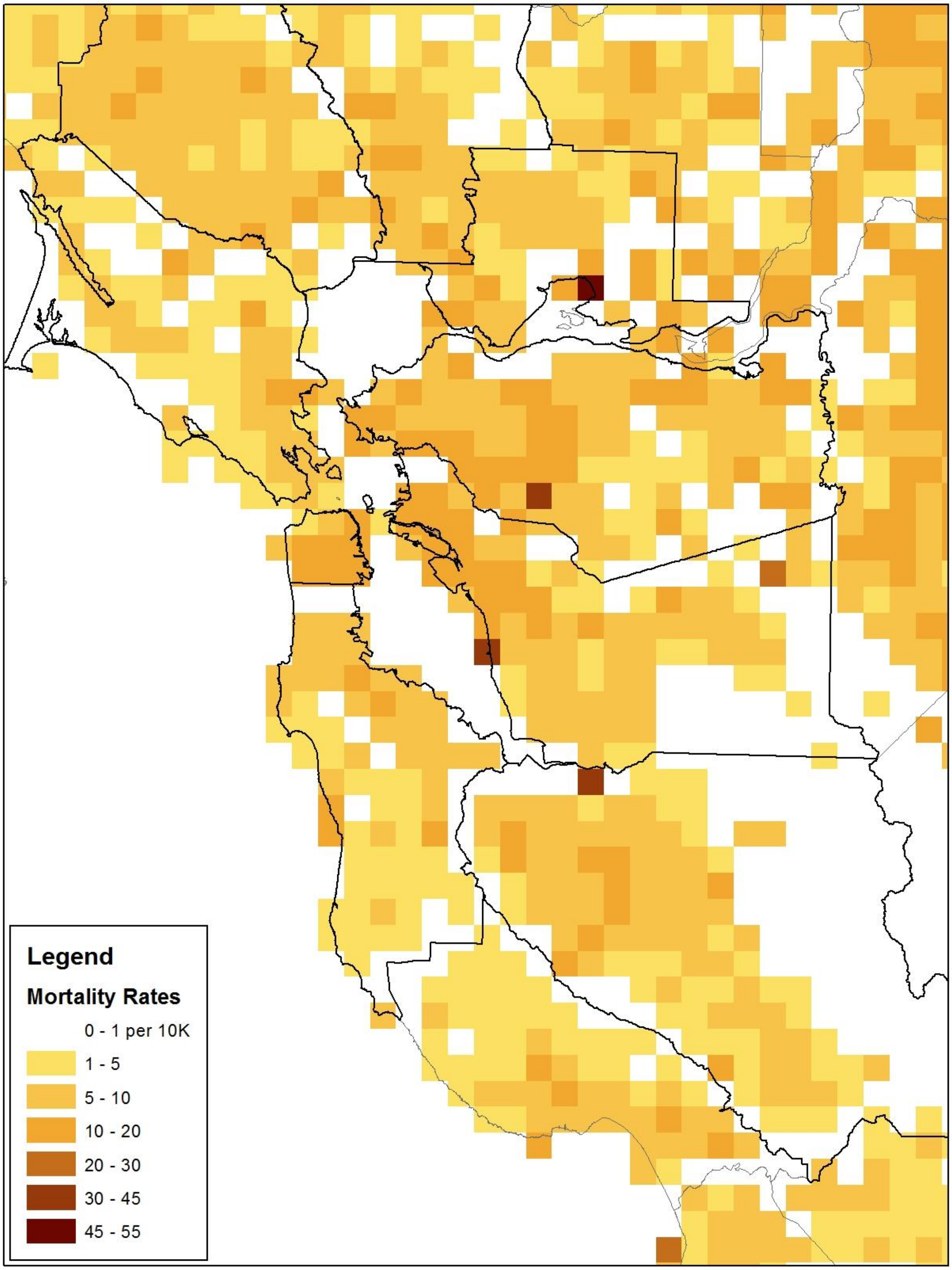


Figure 7. Reduction of mortality rates (incidents per 10K adult population).

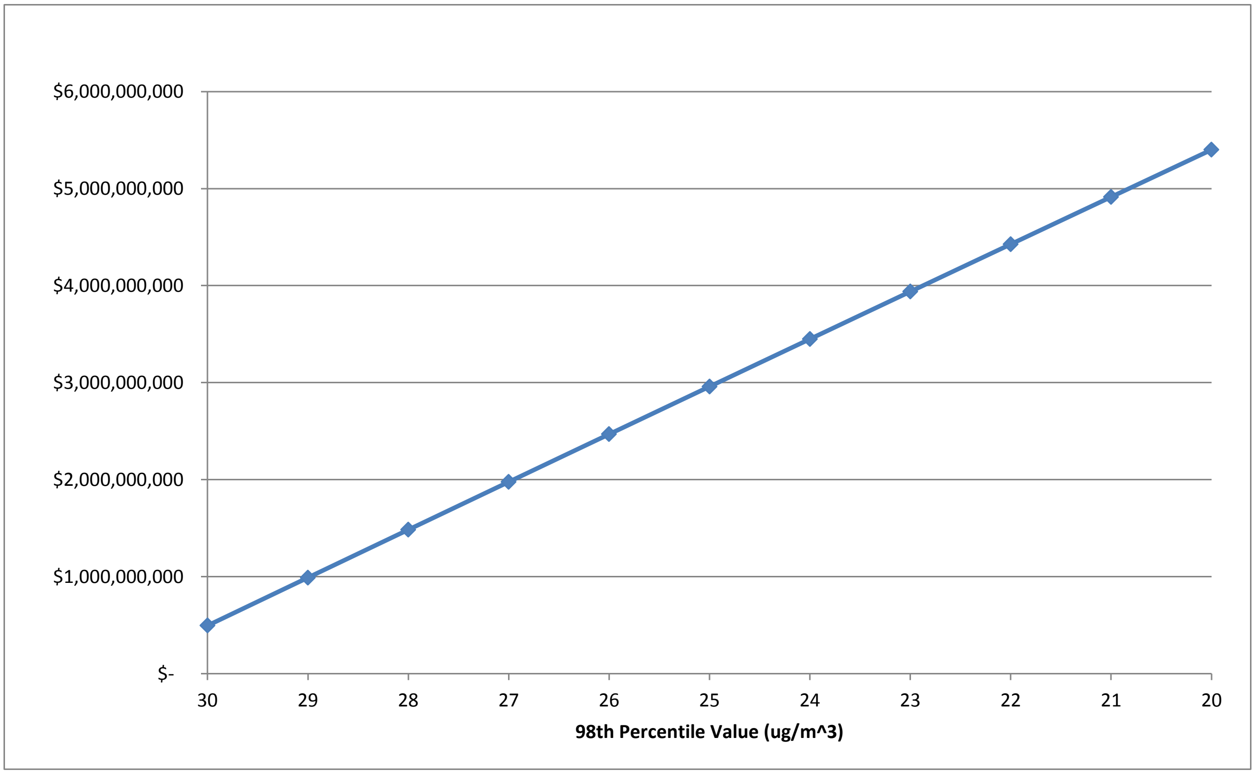


Figure 8. Response of mortality-related valuation to incremental reductions in ambient PM.

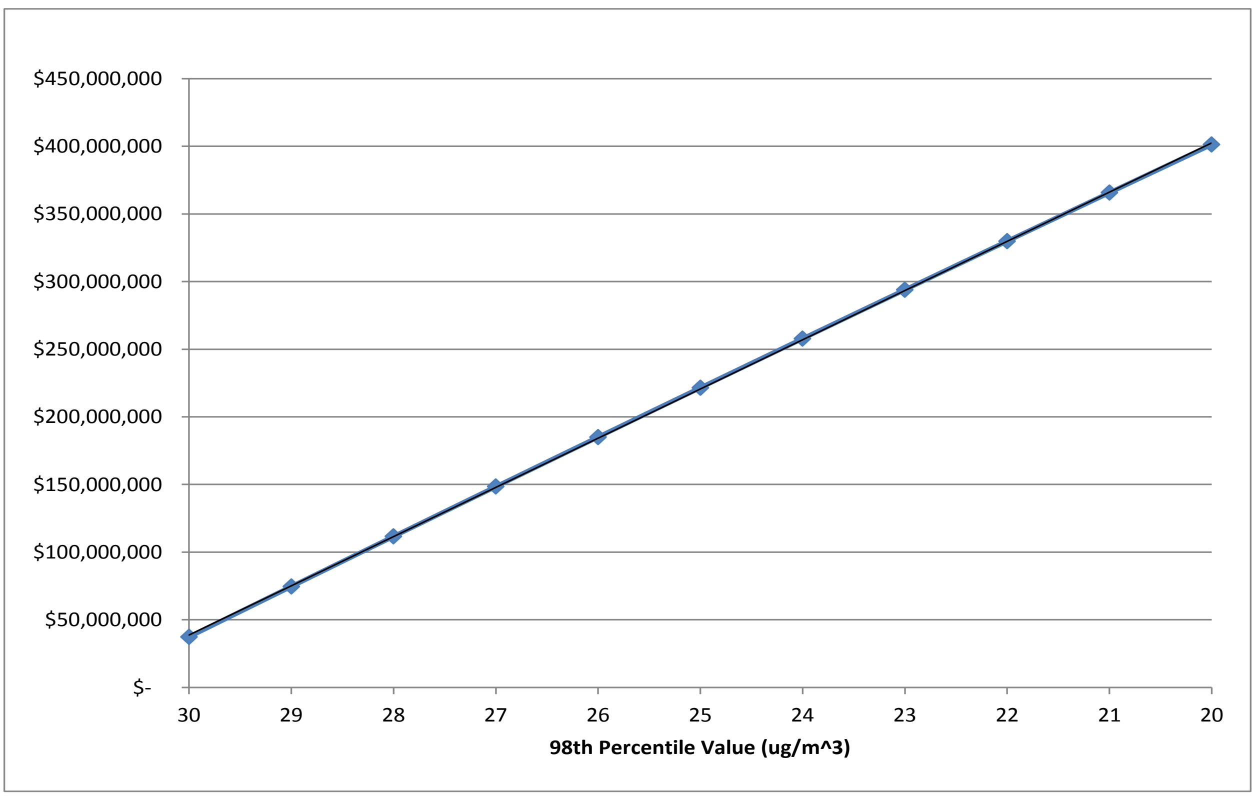


Figure 9. Response of morbidity-related valuation to incremental reductions in ambient PM.

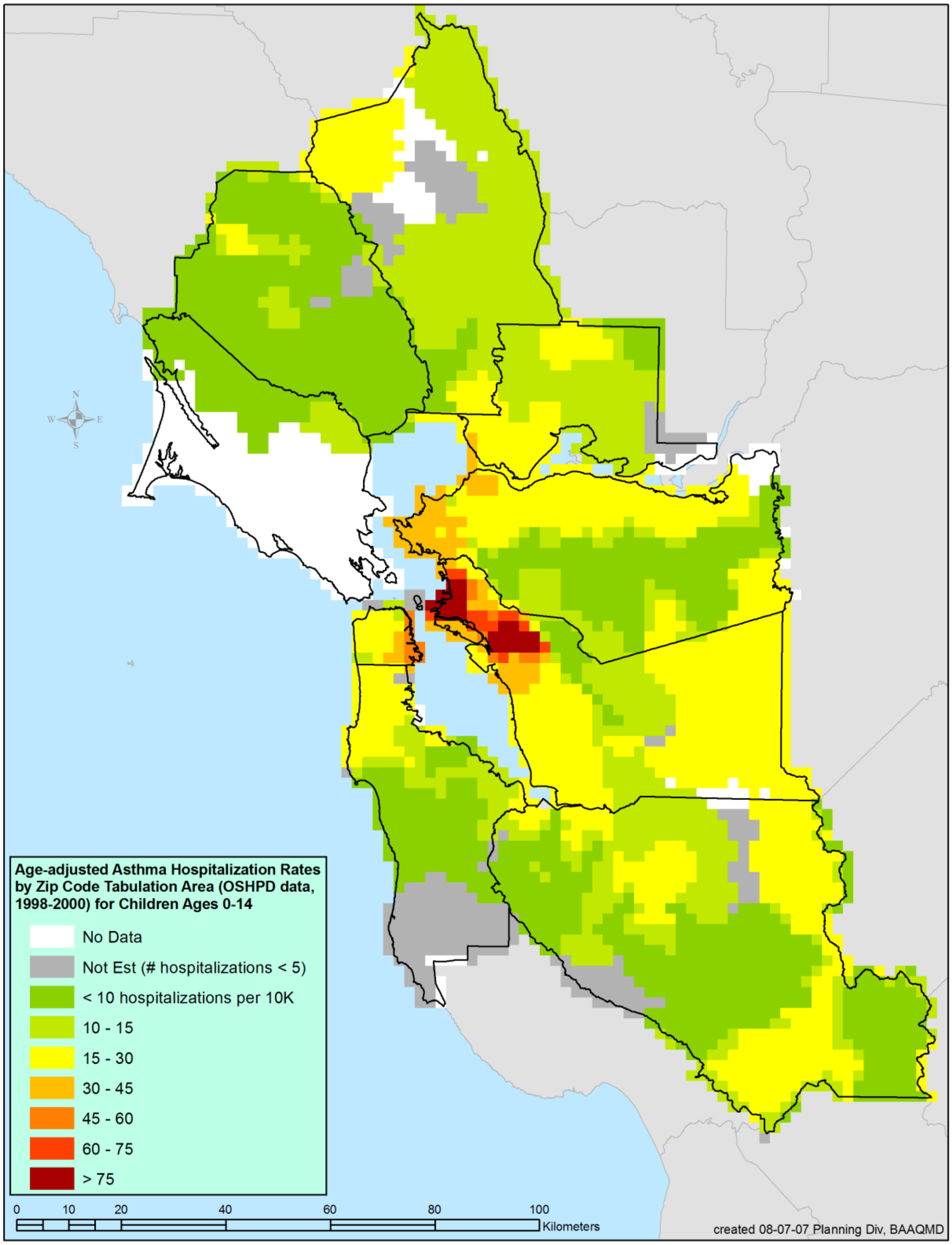


Figure 10. Age-adjusted rates of hospitalization due to asthma in children 14 years of age and below.