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Evaluation of the Effectiveness and Benefits of the Wood Burning Rule in the San Francisco Bay Area for Winter 2009-2010

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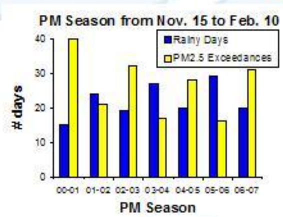

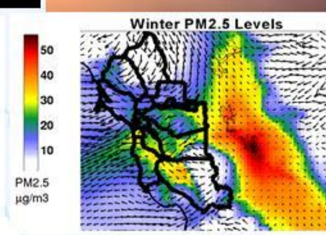

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Evaluation of the Effectiveness and Benefits of the Wood Burning Rule in the San Francisco Bay Area for Winter 2009-2010

1. Introduction

Research and Modeling Section staff have studied the effectiveness of the District's wood burning rule for winter 2009-10, using the following five methods:

1. Chemical Mass Balance (CMB) analysis.
2. PM filter analysis for carbon-14 (^{14}C).
3. Meteorological cluster analysis.
4. Air quality modeling.
5. Health impacts analysis.

For each method, a brief description and a summary of findings are given below. The overall assessment of the effectiveness of the rule for winter 2009-10 is presented in the conclusion section.

2. Background

Seventeen days of interest with their 24-hr $PM_{2.5}$ concentrations at selected Bay Area monitoring stations for winter 2009-10 are given in Table 1. Key features of the tabulated data include:

- Seven Spare the Air days, marked with an S (11/26, 12/9, 12/25, 1/5, 1/8-1/10).
- Nine 24-hour exceedance days, marked with an E (12/10, 12/19, 12/20, 12/26, 1/5-1/8, 1/16).
- Five filter data analysis days for ^{14}C, marked with an F (11/21, 12/3, 12/9, 1/8, 1/14).
- Six CMB analysis days, not marked (12/3, 12/9, 12/15, 1/2, 1/8, 1/14).

Note the following observations:

- Two of the Spare the Air days were also exceedance days (1/5, 1/8).
- Carbon-14 analysis was conducted for two Spare the Air days (12/9, 1/8) and three non-Spare the Air days (11/21, 12/3, 1/14).
- CMB analysis was conducted for two Spare the Air days (12/9, 1/8) and four non-Spare the Air days (12/3, 12/15, 1/2, 1/14).

Table 1. Observed 24-hr $PM_{2.5}$ concentrations ($\mu g/m^3$) on days of interest for winter 2009-10. Exceedances are highlighted. (S= Spare the Air day. E = exceedance day. F=filter analysis day for ^{14}C)

Station Location	Days over National Standard	F 11/21	S 11/26	F 12/3	S/F 12/9	E 12/10	E 12/19	E 12/20	S 12/25	E 12/26	S/E 1/5	E 1/6	E 1/7	S/E/F 1/8	S 1/9	S 1/10	F 1/14	E 1/16
San Rafael	4	7	23	15	19	25	34	30	28	34	**35.7**	**41.0**	**40.6**	**47.0**	24	26	9	35
San Francisco	4	11	23	18	20	28	**35.6**	25	30	27	**36.5**	**41.1**	**45.8**	34	22	26	17	31
Vallejo	2	8.4	33.3	14.3	20.7	18	26.2	**37.1**	33.5	**38.6**	23.5	31.0	25	31.7	29.7	17	9	23
San Jose	2	12.4	22.3	29.8	23.3	35	28.9	23.7	27.1	11.8	35.3	33.3	**41.5**	**35.5**	28.8	29.6	12.5	20
Concord	2	5.5	29.2	21.9	18.4	25.0	23.3	33.9	25.4	**39.0**	30.1	32.3	32.1	19.7	19.7	18.3	5.4	**36.4**
Livermore	1	9.2	19	16.9	21.5	**36.3**	24.5	30.7	29.9	32.2	30.1	28.4	24.7	10	13	8	4	22
Redwood City	1	7.7	17	24	21	32	28	26	24	16	28	30	**36.7**	31	22	23	10	20

3. Chemical Mass Balance Analysis

We performed CMB analyses for three sites – Livermore, Vallejo, and San Jose. At each site, speciated samples were available for the 12/9/09 and 1/8/10 Spare the Air days. Samples were also available for the 12/3/09, 12/15/09, 1/2/10, and 1/14/10 non-Spare the Air days. These latter days were used in comparisons with the Spare the Air days' samples. Two types of comparisons were conducted. The first examined the fraction of total PM2.5 contributed by wood smoke. The second focused on the ratio of wood smoke to total *carbonaceous* PM2.5, which is an indication of the relative contribution of wood smoke to fossil fuel-based PM.

Figure 1a shows the wood smoke contribution to total PM2.5 for 12/9/09 compared with 12/3/09 and 12/15/09. Figure 1b shows the wood smoke contribution to total PM2.5 for 1/8/10 compared with 1/2/10 and 1/14/10. The bottom bar represents the estimated wood smoke portion within total $PM_{2.5}$. Two observations are worth noting. First, wood smoke is a significant (40-60) percent of the total $PM_{2.5}$ at most sites and days examined. These percentages are of similar magnitude to those found in previous CMB analyses. Second, the estimated differences in wood smoke between Spare the Air and non-Spare the Air days are insignificant. The contributions from wood smoke are similar to or higher on 12/9/09 (a Spare the Air day) than the non-Spare the Air days. On the other hand, the wood smoke percentages are lower on 1/8/10 (Spare the Air day) than the non-Spare the Air days.

To determine whether the results on 1/8/10 indicate lower levels of wood burning, we looked at wood smoke as a fraction of carbonaceous $PM_{2.5}$. The results are presented in Figures 2a and 2b. In particular, Figure 2b shows that the proportion of carbonaceous $PM_{2.5}$ due to wood smoke was not significantly lower on 1/8/10 (Spare the Air day). This suggests that the small wood smoke fractions shown in Figure 1b for 1/8/10 are more likely due to increased contributions from secondary PM rather than a big drop in wood burning activity. However, without the re-enforcement of a marker like ^{14}C, there is a good deal of uncertainty in the CMB determination of the wood smoke and fossil fuel fractions so that comparisons of specific Spare the Air and non-Spare the Air days are not reliable.

In summary, the CMB analyses indicate that during the winter of 2009-10, wood smoke continued to be a large component of winter PM in the Bay Area. Furthermore, there is no clear evidence of large-scale compliance with the wood burning ban. Together these findings imply that while curbing wood burning has the potential to significantly affect Bay Area total $PM_{2.5}$, the compliance rate was not sufficient for the benefits to be discernible.

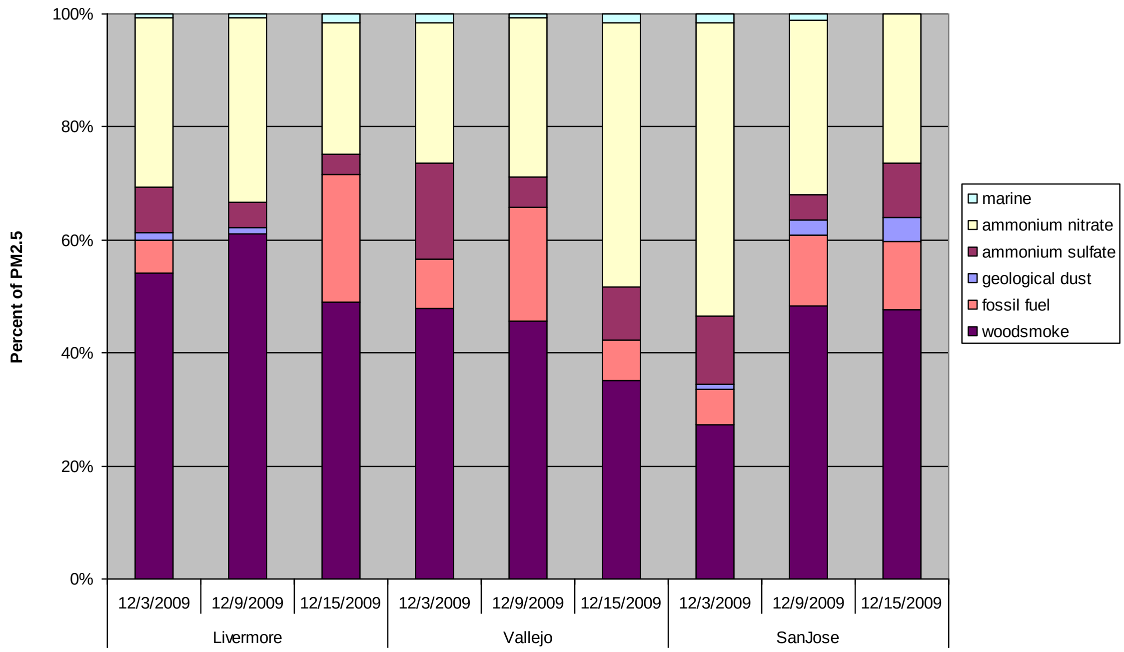


Figure 1a. CMB-estimated percent contributions to total $PM_{2.5}$ for the 12/9/09 Spare the Air day, compared with 12/3/09 and 12/15/09.

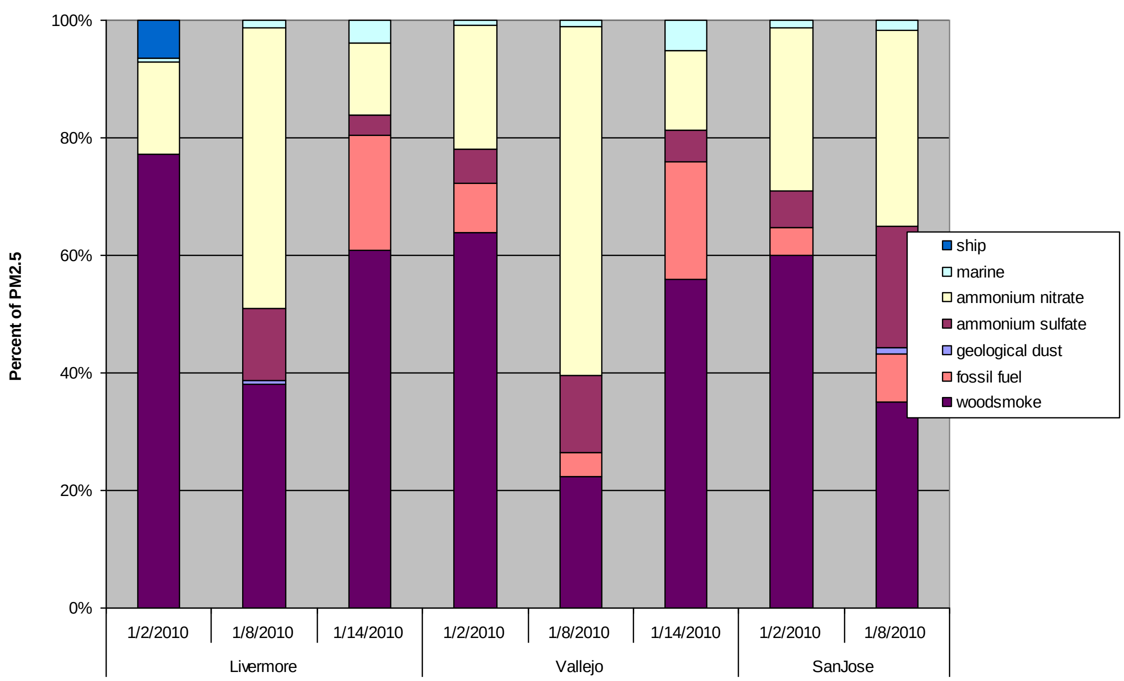


Figure 1b. CMB-estimated percent contributions to total $PM_{2.5}$ for the 1/8/10 Spare the Air day, compared with 1/2/10 and 1/14/10.

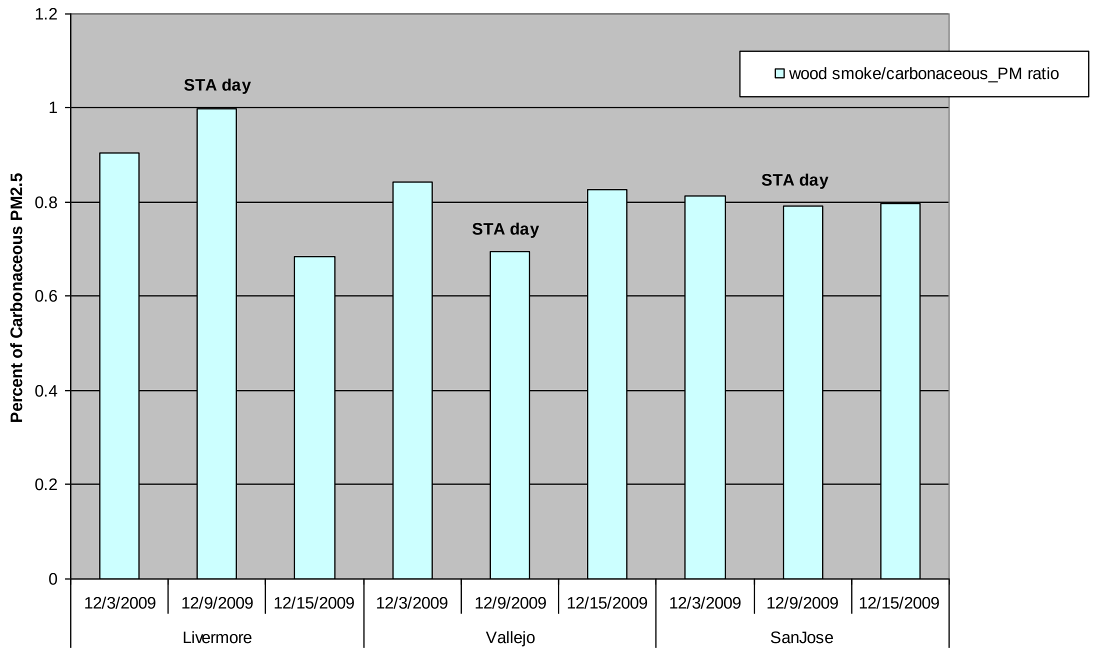


Figure 2a. CMB-estimated percent contributions to carbonaceous $PM_{2.5}$ for the 12/9/09 Spare the Air day, compared with 12/3/09 and 12/15/09.

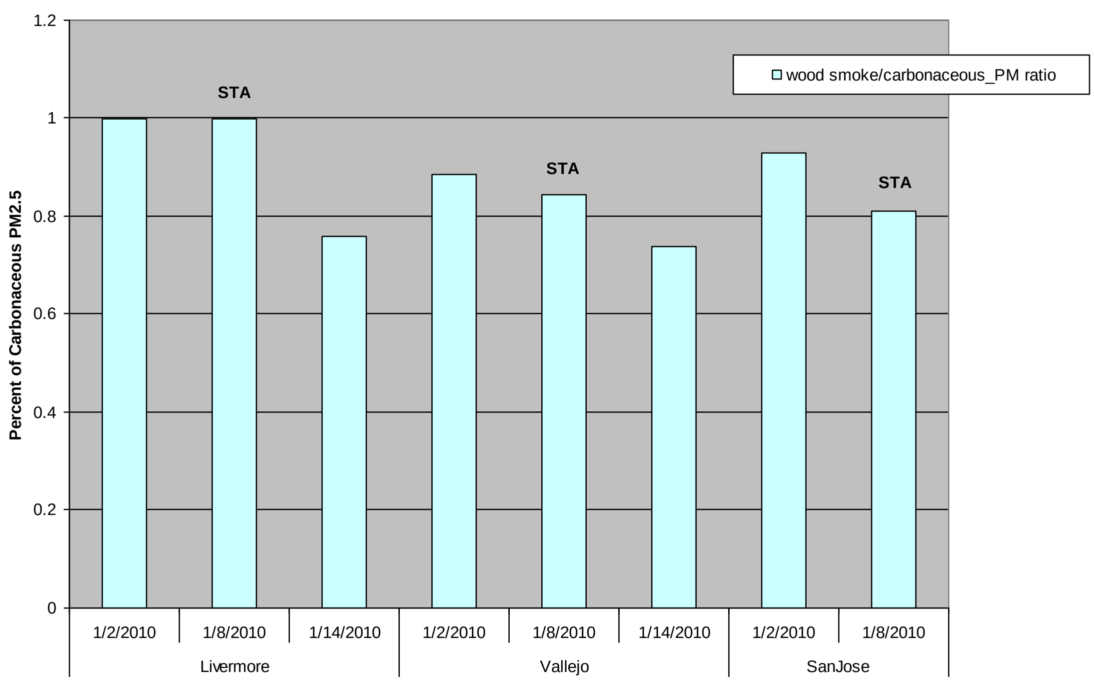


Figure 2b. CMB-estimated percent contributions to carbonaceous $PM_{2.5}$ for the 1/8/10 Spare the Air day, compared with 1/2/10 and 1/14/10.

4. PM Filter Analysis for Carbon-14

Carbon-14 analysis of PM filters is a method used to identify the ratio of new carbon over stable carbon (^{12}C or ^{13}C). It is assumed that the majority of new carbon (under 100 years old) is coming from wood burning, cooking, agricultural burning, and biodiesel consumption.

In order to study the effectiveness of the wood burning rule, we had the University of Arizona analyze PM filters for five days: two spare the Air days and three non-Spare the Air days. PM on Spare the Air days were compared against PM on non-Spare the Air days. The three non-Spare the Air days were selected for comparison because they had meteorological conditions and PM levels similar to the Spare the Air days.

Table 2 shows dates and locations for ^{14}C analysis. Figure 3 shows results from the comparison among Spare the Air and non-Spare the Air days. The comparison of Spare the Air days 12/9 and 1/8 against non-Spare the Air days does not show statistically significant differences among them. Therefore, this method was inconclusive in identifying the effectiveness of the wood burning rule for winter 2009-10.

Table 2. Dates and locations for C^{14} analysis. An "x" indicates that ^{14}C analysis was performed. Last column provides rationale for analyzing each day: selected Spare the Air days were paired against non-Spare the Air days.

Date	Concord	Napa	San Jose	San Rafael	
11/21	x	x	x	x	compare with 12/9
12/03	x	x	x	x	compare with 12/9
12/09	x	x	x	x	Spare the Air call
01/08	x	x	x	x	Spare the Air call
01/14	x	x	x	x	compare with 1/8

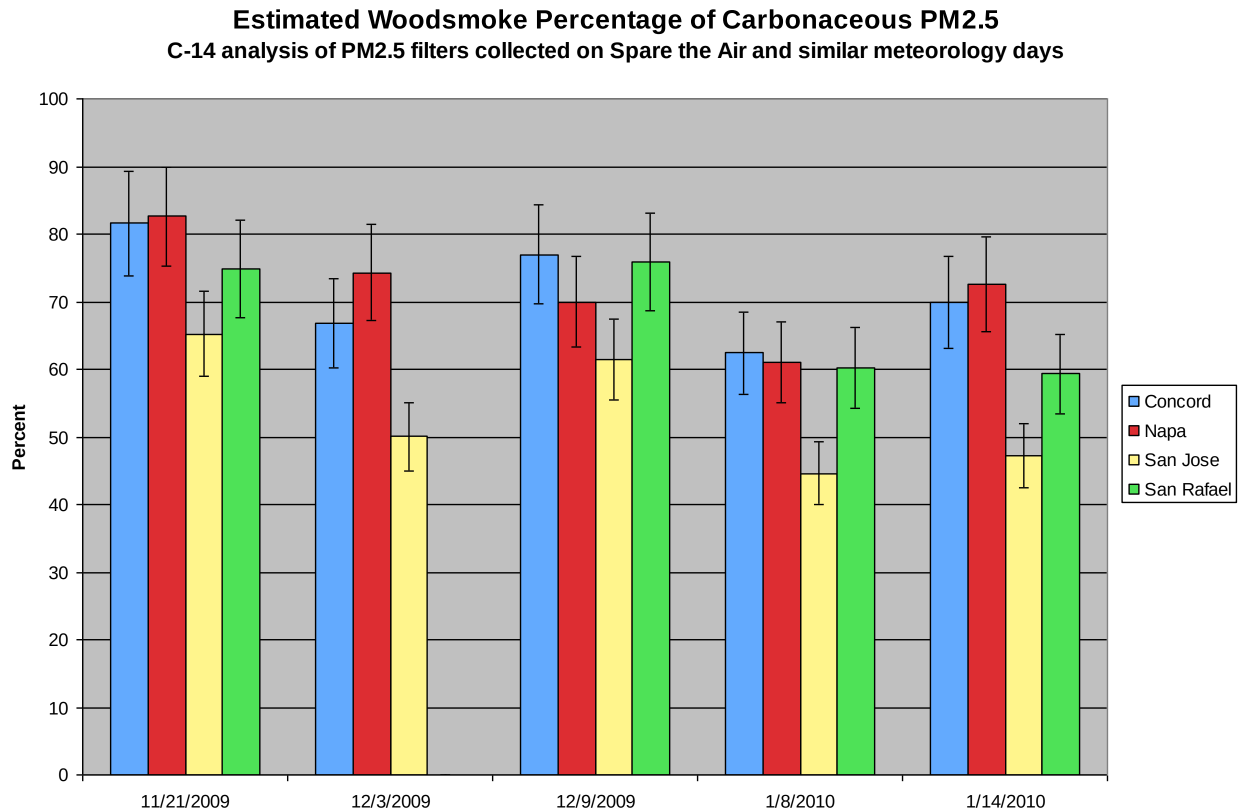


Figure 3. Results of ^{14}C sampling for dates and locations indicated in Table 2.

5. Meteorologically-Adjusted $PM_{2.5}$ Trend Analysis

This method is applied for ten winter seasons (2000-01 through 2009-10) to estimate the number of PM-conducive and exceedance days. (Conduciveness is determined based on meteorological conditions.) Then for each season and each PM observation station, the percentages of conducive days with observed PM2.5 levels exceeding 35 $\mu g/m^3$ were calculated. Trends in percentages over these winters are expected to show whether air quality is improving, staying the same or getting worse.

Because the number of exceedance days in the Bay Area is small, we repeated the analysis above with observed PM2.5 levels exceeding 25 $\mu g/m^3$ as well. The above calculations are referred to as p35 and p25 below.

Lower percentages for the last two winters (after wood smoke rule promulgation) relative to 2000-01 through 2007-08 (before wood smoke rule promulgation) would provide partial evidence for the effectiveness of the rule. Note that the trend analysis described here applies to winter seasons only. Also, the sample size for Spare the Air days from the last two winters is not large enough to facilitate comparisons of Spare the

Air days against non-Spare the Air days directly. It will be possible to make the Spare the Air day versus non-Spare the Air day comparison in the future after obtaining sufficiently large sample size for the Spare the Air days.

The results from this exercise are shown in Table 3. Excluding the outlier winters 2000-01 and 2007-08, trends do appear evident. For most locations, the p_{25} and often also the p_{35} values were in a lower range for 2008-09 and 2009-10 as compared to the previous years.

Trends for p_{25} and p_{35} at San Jose are plotted in Figure 4. The six winters before the wood smoke rule promulgation exhibited p_{25} ranging 42-85% with a mean of 70%. The two years after the wood smoke rule promulgation exhibited smaller p_{25} values of 35% and 36%. Likewise, p_{35} ranged 19-50% during 2001-02 through 2006-07. On average, before the wood smoke rule promulgation, there were around 5.8 days per winter season for which San Jose 24-hr $PM_{2.5}$ level exceeded the NAAQS threshold. During the two winters after the wood smoke rule promulgation, only a single conducive day exhibited San Jose $PM_{2.5}$ levels exceeding the NAAQS 24-hr $PM_{2.5}$ threshold. San Jose was an ideal location to evidence the effectiveness of the wood smoke rule because this location was believed to be heavily impacted by wood smoke. Therefore, it would be expected to have benefited considerably from compliance with the rule.

Locations that were less strongly impacted by wood smoke would be less likely to have benefited from the rule. For example, the p_{25} and p_{35} values for San Francisco were in the same range, and occasionally even lower, for 2001-02 through 2006-07 relative to the more recent years for which the wood smoke rule was in effect. These data do not provide any evidence for a trend around San Francisco. The lack of a trend at San Francisco likely resulted because wood smoke emissions were less of a contributor to local $PM_{2.5}$ than at many other monitoring locations. Likewise, Vallejo exhibited some overlap for its ranges of p_{25} and p_{35} values before and after the wood smoke rule promulgation. The lack of a trend at Vallejo likely resulted because this location was believed to be the most strongly impacted by secondary $PM_{2.5}$ transported from the Central Valley.

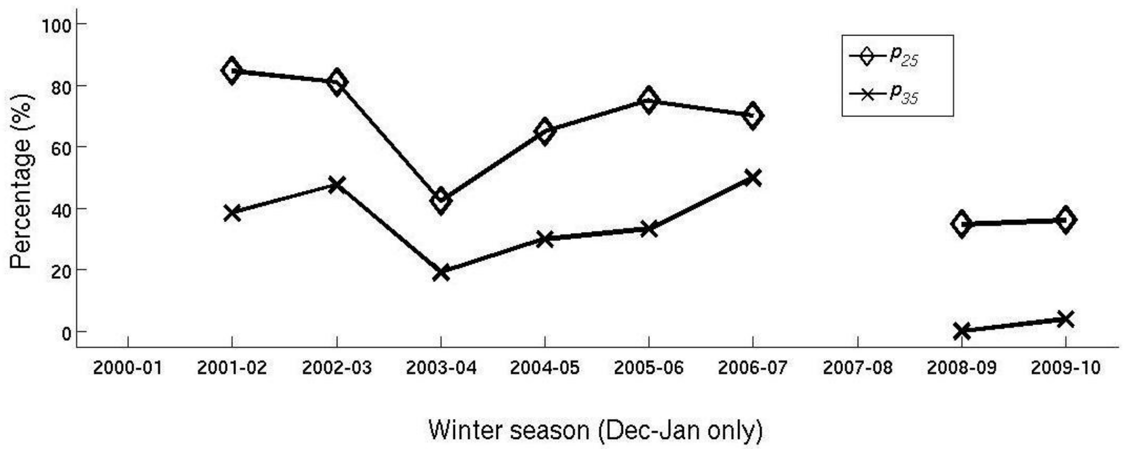


Figure 4. Time series for p_{25} and p_{35} for San Jose, taken from Table 3. Outlier winters 2000-01 and 2007-08 to be excluded from the trend analysis are not shown.

Table 3. Number of December-January conducive days having $PM_{2.5}$ level measurements (N) and percentages of these days for which 24-hr $PM_{2.5}$ level exceeded 25 and 35 µg/m3 (p_{25} and p_{35}, respectively) for six Bay Area monitoring locations across ten winters. Wood burning restrictions were in effect only for 2008-09 and 2009-10. Outlier winters to be excluded from trend analysis are: 2000-01 (red) was extremely favorable to PM2.5 buildup, and 2007-08 (blue) exhibited few conducive days. N/A indicates no measurements available for that location and winter.

	Concord (FRM)			Livermore			Oakland			Redwood City			San Francisco			San Jose			Vallejo		
	N	p_{25}	p_{35}	N	p_{25}	p_{35}	N	p_{25}	p_{35}	N	p_{25}	p_{35}	N	p_{25}	p_{35}	N	p_{25}	p_{35}	N	p_{25}	p_{35}
2000-01	20	80%	55%	21	90%	71%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	21	95%	90%	N/A	N/A	N/A
2001-02	13	54%	15%	13	23%	0%	N/A	N/A	N/A	N/A	N/A	N/A	4	25%	0%	13	85%	38%	N/A	N/A	N/A
2002-03	19	58%	37%	21	52%	33%	21	67%	52%	N/A	N/A	N/A	20	55%	25%	21	81%	48%	18	72%	39%
2003-04	24	29%	8%	26	31%	8%	26	23%	8%	18	33%	11%	26	27%	15%	26	42%	19%	26	46%	15%
2004-05	22	55%	14%	25	32%	8%	25	60%	20%	25	60%	8%	25	52%	8%	20	65%	30%	25	40%	0%
2005-06	12	42%	25%	12	50%	25%	8	38%	13%	12	42%	17%	12	25%	17%	12	75%	33%	12	67%	50%
2006-07	9	56%	11%	10	70%	30%	10	80%	30%	10	50%	20%	10	40%	0%	10	70%	50%	10	60%	10%
2007-08	4	0%	0%	4	25%	0%	4	25%	0%	4	25%	0%	4	25%	0%	4	50%	25%	4	25%	0%
2008-09	23	26%	4%	21	14%	0%	23	30%	4%	23	26%	0%	23	52%	9%	23	35%	0%	23	43%	17%
2009-10	21	38%	5%	25	8%	0%	13	15%	0%	25	28%	4%	25	40%	16%	25	36%	4%	25	20%	0%

6. Simulations

To estimate the impact of Spare the Air days, two types of simulations were conducted from 11/15/2009 to 1/20/2010 using CAMx. The simulation period contained all seven Spare the Air days of the 2009-10 winter PM season. Two different model runs were performed: (1) with full Bay Area wood burning emissions and (2) with 50 percent reduced wood burning emissions, assuming a 50 percent compliance rate.

In the first run, ambient concentrations with full wood burning emissions were simulated for all days of the simulation period. In the second run, ambient concentrations were estimated will full wood burning emissions on burn days and with 50 percent of wood burning emissions on no-burn days.

Results for two Spare the days (12/9/2009 and 1/5/2010) are shown as an example in Figure 5. Without burning restrictions, peak wood smoke levels of 20-28 $\mu g/m^3$ would have occurred over parts of the East Bay and Santa Clara County. Wood smoke levels would have been around 5 $\mu g/m^3$ or more for many of the remaining populated locations within the Bay Area. Without wood burning restrictions on 12/9/2009, wood smoke levels would have been highest in the South Bay. Without wood burning restrictions on 1/5/2010, wood smoke levels would have been highest in the East Bay.

With burning restrictions on these Spare the Air days, considerable reductions in wood smoke levels would occur for most Bay Area locations near concentrated wood burning source areas. Peak benefits are estimated to be about 10 $\mu g/m^3$ of reduction in $PM_{2.5}$ from wood smoke. Greater benefit would be obtained in the East Bay on 1/5/2010 whereas the South Bay would see slightly greater benefit on 12/9/2009. Wood smoke levels are not reduced to zero because carried over wood smoke from previous days impact the Spare the Air days. In summary, the burning restrictions have a significant effect which varies by location depending on the prevailing weather.

Two examples of estimated impacts are given in Figures 6 and 7 for San Jose and Concord, respectively. Figure 6a shows expected $PM_{2.5}$ levels had the wood burning rule not been in effect (0 percent compliance) while Figure 6b shows expected $PM_{2.5}$ levels had the compliance rate been 50 percent. These figures suggest if 50 percent compliance were achieved, one of the two official exceedances in San Jose might have been avoided. Figures 7a and 7b show analogous representations for Concord. At this location, no Spare the Air days were on the cusp of an exceedance. Nevertheless, larger benefits are expected at Concord than San Jose for the period modeled.

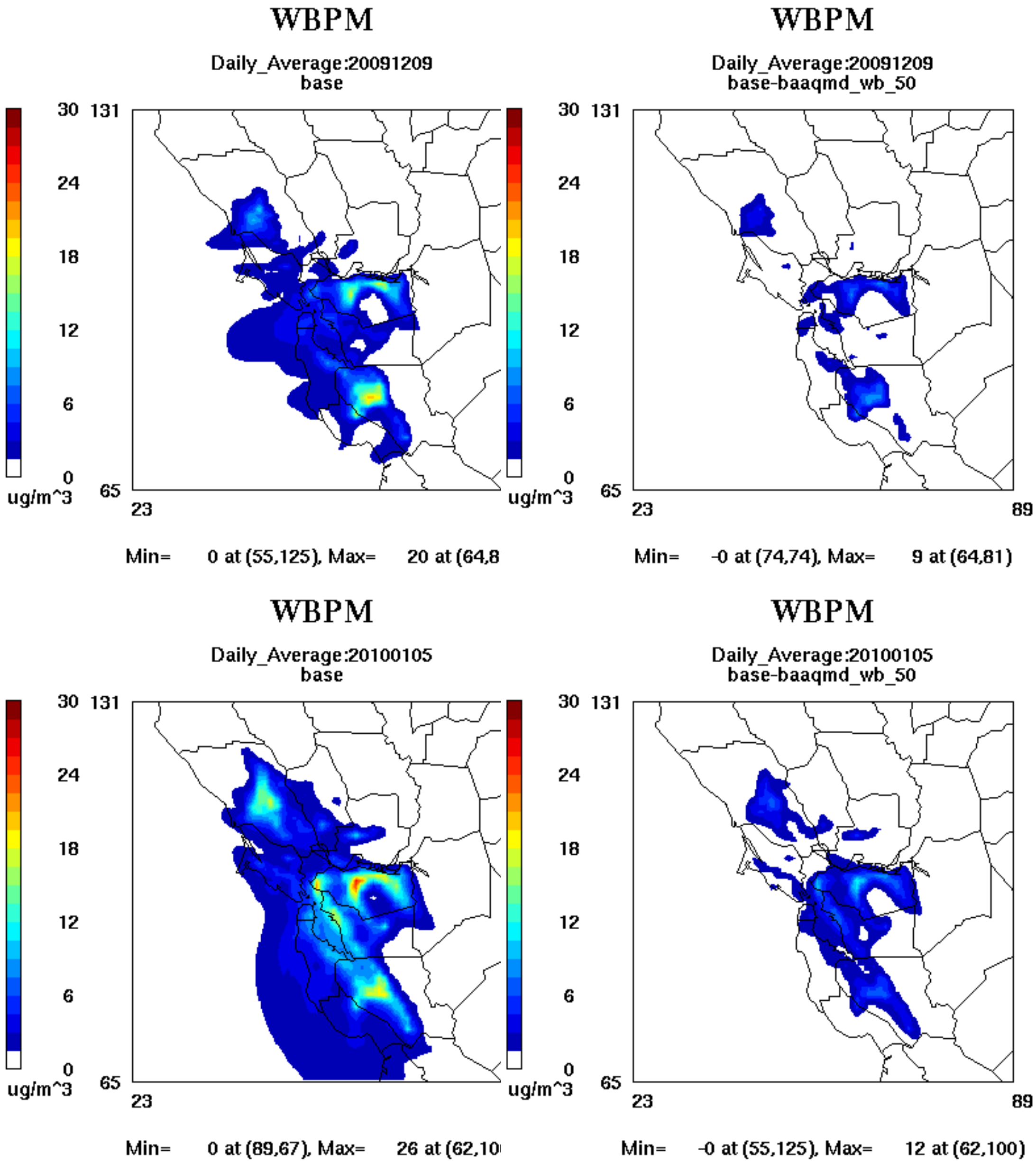


Figure 5. Wood smoke simulation results for Spare the Air days 12/9/2009 (top row) and 1/5/2010 (bottom row). Simulation without wood burning rule (left column) shows estimated Bay Area wood smoke levels assuming full wood burning. Figures in the right column shows estimated benefit (reduction) of wood smoke levels resulting from 50 percent compliance with the burning restrictions.

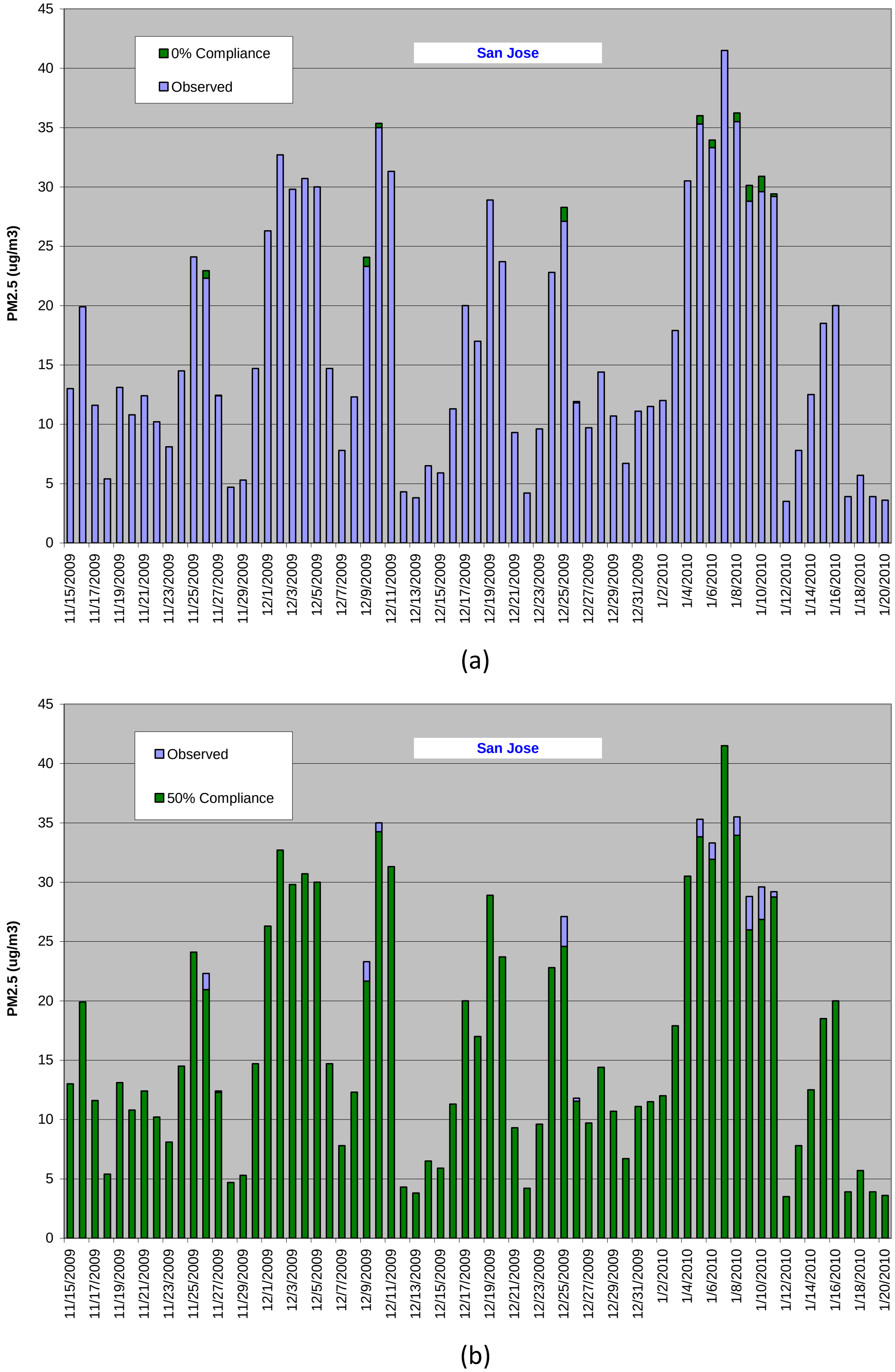
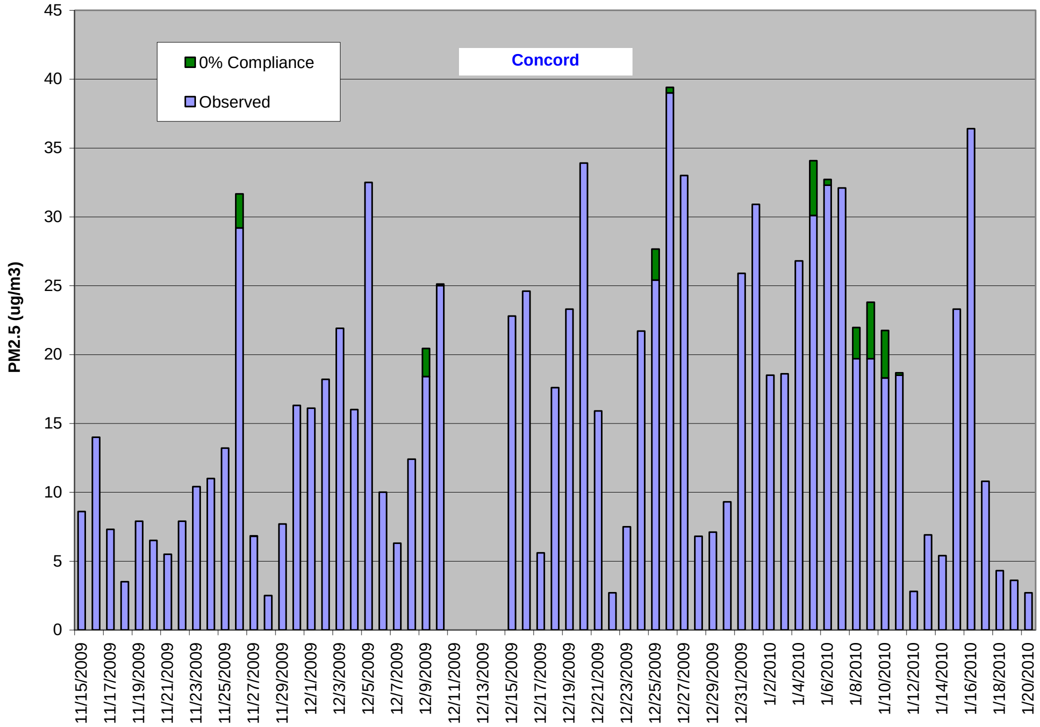
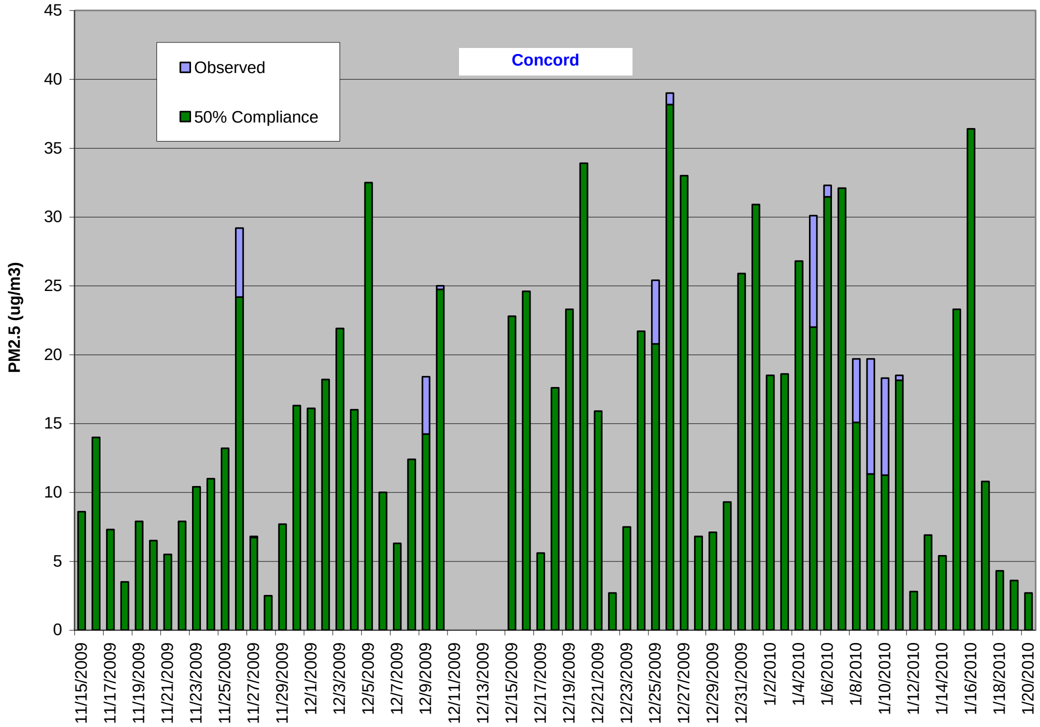


Figure 6. Simulated impacts of wood burning rule at San Jose. (a) 0% compliance; (b) 50% compliance



(a)



(b)

Figure 7. Simulated impacts of wood burning rule at Concord. (a) 0% compliance; (b) 50% compliance

7. BenMap Analysis

BenMap was developed by the U.S. EPA to estimate the impacts of air pollution on human health, in terms of both reductions in the incidence of adverse health effects and monetary benefits. Staff applied BenMap to estimate the impacts of the District's wood burning rule on public health in the San Francisco Bay Area.

PM concentrations from the base case simulation and simulation with assumed 50-percent wood burning compliance rate were input to BenMap. The simulations were conducted for the winter PM season (November 15, 2009 through January 20, 2010). However, BenMap expects concentrations estimated for the entire year. In order to prepare inputs to BenMap, we made two assumptions. First, the mean of simulated daily average concentrations from January 12 through January 20, 2010 was assumed for each day from January 21 through February 28. Second, it was assumed that wood burning emissions are negligible from March 1 through November 14 and the concentration was set to zero for all days in that period.

BenMap allows users to select from a wide array of health impact functions and valuation methods in order to estimate incidence of adverse health effects and monetary value. For this analysis, we used the combination of functions that was used by EPA to evaluate the benefits of the most recent $PM_{2.5}$ National Ambient Air Quality Standards. We assumed the no-threshold scenario as recommended by the EPA Science Advisory Board Advisory Council for Clean Air Compliance.

Table 4 below shows the results of the BenMap analysis. The estimated total benefit of seven no-burn days with 50 percent compliance rate is about $256 million. This value accounts for the list of health effect endpoints shown in the table, including mortality. Furthermore, the monetary values shown represent the willingness-to-pay (WTP) which is at least the direct cost of illness, but can also include the amount a population is willing to pay to avoid the adverse health effects altogether. Table 5 shows the benefits by county. These trends are determined mainly by a combination of pollution level and population density. Age and income distributions are also influential factors.

Table 4. BenMap-estimated monetary benefits of the wood burning rule during the winter 2009-10.

Health Endpoint Group	Valuation
Acute Bronchitis	$ 1,996.00
Acute Myocardial Infarction	$ 2,823,666.00
Acute Respiratory Symptoms	$ 904,697.00
Asthma Exacerbation	$ 15,697.00
Chronic Bronchitis	$ 5,225,826.00
Emergency Room Visits, Respiratory	$ 2,177.00
Hospital Admissions, Cardiovascular	$ 189,849.00

Hospital Admissions, Respiratory	$ 43,049.00
Lower Respiratory Symptoms	$ 6,215.00
Mortality	$ 246,416,955.00
Upper Respiratory Symptoms	$ 7,805.00
Work Loss Days	$ 539,210.00
Grand Total	**$ 256,177,142.00**

Table 5. Monetary benefits by county.

County	**Valuation**
Alameda	$ 57,932,056.00
Contra Costa	$ 60,102,734.00
Marin	$ 8,893,318.00
Napa	$ 2,688,549.00
San Francisco	$ 19,672,059.00
San Mateo	$ 20,972,445.00
Santa Clara	$ 63,976,877.00
Solano	$ 5,495,570.00
Sonoma	$ 16,443,534.00
Grand Total	**$ 256,177,142.00**

Table 6 summarizes the number of averted incidents by health endpoint group. These estimates correspond to the valuations presented above, namely they represent the number of adverse health outcomes averted due to a 50 percent compliance rate for the wood burning rule during the 2009-10 winter season.

Table 6. Reductions in adverse health effect incidence due to 50 percent compliance rate.

Health Endpoint Group	**Reduction in Incidence**
Acute Bronchitis	29
Acute Myocardial Infarction	22
Acute Respiratory Symptoms	15287
Asthma Exacerbation	309
Chronic Bronchitis	13
Emergency Room Visits, Respiratory	4
Hospital Admissions, Cardiovascular	8
Hospital Admissions, Respiratory	3
Lower Respiratory Symptoms	338
Mortality	37
Upper Respiratory Symptoms	253
Work Loss Days	2580

8. Conclusion

Five methods were applied to evaluate the effectiveness of the District's wood burning rule for winter 2009-10. Some of these analyses aimed to quantify the benefits while others gave a measure of the potential benefits. CMB analysis and carbon-14 PM filter analysis did not confirm the impacts of the rule. Trends analysis sought to confirm the realized impacts of the rule for the season as a whole. Wood burning PM simulations and monetary benefits analysis using BenMap were geared toward estimating impacts of the wood burning rule in context.

CMB analysis did not detect significant differences in wood smoke levels between Spare the Air and non-Spare the Air days. Carbon-14 analyses of 20 filter samples representing two Spare the Air and three non-Spare the Air days also did not find differences between the two types of days. An analysis of total PM2.5 trends across several years showed an apparent drop in ambient levels on PM-conducive days with the adoption of the wood burning rule. But the two years of the rule's implementation are insufficient to make conclusive statements regarding the trend. These findings may also suggest an overall drop in wood burning activity rather than specific effects of Spare the Air alerts. This is generally confirmed through surveys and surveillance efforts, which have been documented elsewhere.

The simulated impact with 50 percent compliance rate and the resulting BenMap analysis show significant benefits. Recent survey studies suggest that the actual compliance rate was about four percent, rather than 50 percent. In that case, the tables presenting the simulated PM values and the resulting health benefit may be about 12 times less than the values presented in the tables for these two categories.

9. Discussion

The meteorologically-adjusted trend analysis suggested that $PM_{2.5}$ levels decreased upon the promulgation of the wood smoke rule for many Bay Area locations. The decrease in $PM_{2.5}$ levels was generally largest for locations believed to have been most heavily impacted from wood smoke. The trend was less strong or even absent for locations for which wood smoke was believed to have been less of a contributor to $PM_{2.5}$. This spatial pattern for the $PM_{2.5}$ trends to decrease more strongly around areas with more wood burning emissions suggested that decreasing (total) $PM_{2.5}$ levels indeed reflected decreasing wood smoke $PM_{2.5}$ levels. Thus, overall, the meteorologically-adjusted trend analysis does suggest the rule has been effective to reduce both $PM_{2.5}$ levels and the 24-hr $PM_{2.5}$ NAAQS exceedance rate. The effectiveness of the rule varied strongly with location, however, presumably due to spatial variability for the wood burning emissions. It is cautioned that other factors such as changes in economic activity or non-wood burning emissions may have also contributed to the observed trends.

The meteorologically-adjusted trend analysis described herein provided the best available means to isolate changes in $PM_{2.5}$ level trends over a relatively short two-winter period. Nonetheless, any trend analysis based on such a small sample size may be inaccurate or even misleading. This meteorologically-adjusted trend analysis will be repeated after future winters to increase the sample size. Conclusive evidence for a downward trend in $PM_{2.5}$ levels would likely require at least an additional one to three years of measurements.

Note that although the CMB results show wood smoke to be a large fraction of total PM on some days, the modeling suggests that eliminating that fraction requires consecutive Spare the Air alerts on the preceding days and not just on the target day. For instance, CMB analysis shows wood smoke to be ~11 $\mu g/m^3$ in San Jose on 1/8/2010, but Figure 6b shows the simulated benefit, at 50 percent compliance, to be nowhere near a 4-5 $\mu g/m^3$ reduction in total $PM_{2.5}$. Carryover effects are important as can be seen on 1/9 and 1/10, both Spare the Air days. The same phenomenon is present at Concord (Figure 7b).

These analyses are planned for the next several years as the sample size (the number of no-burn days) increases. This will reduce uncertainties associated with them.