EVALUATION OF SACRAMENTO METROPOLITAN AIR QUALITY MANAGEMENT DISTRICT'S "CHECK BEFORE YOU BURN" PROGRAM

FINAL REPORT
STI-909014.06-3612-FR2

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May 6, 2009
Updated August 24, 2009

ACKNOWLEDGMENTS

The authors of this report thank several Sonoma Technology, Inc. staff who contributed to this project: Hilary Hafner and Paul Roberts for their scientific advice and guidance; Charley Knoderer for creating the air quality climatology plots used in this report; and Steve Reid and Sandy Smethurst for editing this report.

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1. INTRODUCTION

On October 25, 2007, the Sacramento Metropolitan Air Quality Management District (SMAQMD) adopted Rule 421, Mandatory Episodic Curtailment of Wood and Other Solid Fuel Burning. The rule established a burning curtailment program with three messages and/or restrictions that are distributed to the public before a possible curtailment. The message/restriction depends on the "next-day" 24-hr average $PM_{2.5}$[1] concentration forecast for Sacramento County, which is issued every day by 11 a.m. The messages/restrictions based on the forecasted concentrations follow:

- $PM_{2.5}$ forecast >25 µg/m^3 to ≤35 µg/m^3: Voluntary curtailment during which burning is discouraged.
- $PM_{2.5}$ forecast >35 µg/m^3 to ≤40 µg/m^3: Stage 1 mandatory curtailment, during which no burning is allowed except in U.S. Environmental Protection Agency (EPA)-certified woodstoves and inserts or pellet stoves.
- $PM_{2.5}$ forecast >40 µg/m^3: Stage 2 mandatory curtailment during which no burning is allowed in any device.

Rule 421 is in effect each "winter" from the beginning of November through the end of February. The rule has been in place for two "winters". However, for the first "winter" of the program, the rule was in effect from December 1, 2007 through the end of February 2008.

The primary objective of the work described in this report is to (1) determine the effectiveness of Rule 421 in reducing $PM_{2.5}$ concentrations in Sacramento County; and (2) to provide information that can be used to determine whether any program changes should be considered to help Sacramento County attain National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$. This work was divided into two phases: (1) Phase I results are presented in this report and (2) Phase II work will take place during summer 2009 and findings will be reported in September 2009.

Several questions were posed by SMAQMD and addressed by Sonoma Technology, Inc. (STI) in Phase I:

- What is the effectiveness of the burning curtailment program toward meeting the NAAQS?
- Does chemical mass balance modeling (CMB)[2] confirm the effectiveness findings?
- Was the 2008/2009 wood-burning season representative of normal $PM_{2.5}$ concentrations?
- What should the no-burn threshold be to help reduce $PM_{2.5}$ below the NAAQS?
- Should no-burn days be called on the day prior to forecasted high-$PM_{2.5}$ concentration days (days expected to exceed NAAQS) to help lower pollution during $PM_{2.5}$ episodes?

[1] $PM_{2.5}$ includes particles in the air that are less then 2.5 microns in diameter.
[2] CMB modeling uses observations of $PM_{2.5}$ species and the known abundances of chemical species from emission sources (e.g., wood burning, automobile exhaust, dust, etc.) to determine the contribution from each source type to each measured $PM_{2.5}$ daily sample.

To address these questions, STI performed a combination of numerical modeling, CMB modeling, and data analysis to develop weight-of-evidence findings on the effectiveness of Rule 421 in reducing ambient $PM_{2.5}$ concentrations. This approach provides greater certainty in the findings compared to those uncertainty findings based on modeling or analysis alone. A similar approach is being taken by the Bay Area Air Quality Management District (BAAQMD) and was taken by the San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) to address the effectiveness of their no-burn programs.

After completing the work presented in the body of this report, STI conducted modeling analyses to provide additional information to address the question: "What is the effectiveness of the burning curtailment program toward meeting the NAAQS?" The findings from the additional analyses are provided in Appendix A and are consistent with the results of the data analysis described in the main body of the report. The addition of Appendix A is the reason this report was updated on August 24, 2009.

2. SUMMARY OF FINDINGS

Answers to the key questions posed by SMAQMD are summarized in this section. Additional details of Phase I findings can be found in Section 4.

Question 1: What is the effectiveness of the burning curtailment program toward meeting NAAQS?

Answers:

1. Daily $PM_{2.5}$ data collected by Beta Attenuation Monitors (BAMs)[3] show that the NAAQS threshold of 35.5 μg/m^3 was exceeded on 20 days during the 2008/2009 winter. Analysis of a limited number of days[4] indicated that without Rule 421 there would have been about 13 additional days on which the NAAQS was exceeded.
2. Data analysis results of a limited number of days[2] show the average reduction of the daily 24-hr average $PM_{2.5}$ concentration on
   a. Stage 1 days was about 4 μg/m^3 or 10% of the total $PM_{2.5}$ concentration and
   b. Stage 2 days was about 12 μg/m^3 or 23% of the total $PM_{2.5}$ concentration.
3. Data analysis results show the greatest reduction of $PM_{2.5}$ concentrations resulting from a burn ban occurred during the evening hours. The average reduction during the evening on
   a. Stage 1 days was 19 μg/m^3 and
   b. Stage 2 days was 23 μg/m^3.
4. Data analysis results suggest that, without a burn ban, the change in the concentration from the day prior would have been greater. The average change in the 24-hr daily average concentration from a day prior on
   a. Stage 1 days was 5 μg/m^3 greater and
   b. Stage 2 days was 17 μg/m^3 greater.

[3] Official NAAQS exceedance days for non-attainment designation are based on Federal Reference Monitor (FRM) data. To be NAAQS compliant for $PM_{2.5}$, about two days per year can exceed NAAQS assuming samples taken every third day and about 5 days if the sampling frequency were daily.

[4] Eleven day-pairs were analyzed to derive this result. Each day-pair consists of two days with similar meteorology: one day on which a Stage 1 or Stage 2 burn ban was issued and a second day on which no burning restrictions were imposed. Therefore, for each day-pair, differences in $PM_{2.5}$ concentrations between days could be primarily attributed to a Stage 1 or Stage 2 burn ban. Because of the limited number of day-pairs, the results derived from analysis should be viewed as rough approximations.

Question 2: Does CMB modeling confirm the effectiveness findings?

Answers:

1. Review of CMB output indicates that the average wood smoke contribution on days when $PM_{2.5}$ concentrations were high was at least 9.4 $\mu g/m^3$, or 25% of the total $PM_{2.5}$ concentration,[5] and was as high as 19 $\mu g/m^3$, or 40%, on individual days. These results indicate that it is possible to achieve a $PM_{2.5}$ reduction on the order of 10 to 20 $\mu g/m^3$ through the curtailment of wood burning and support Question 1 findings.
2. Review of CMB output indicates that the average reduction of the daily 24-hr average $PM_{2.5}$ concentration for Stage 1 and Stage 2 days combined was 1.5 $\mu g/m^3$, or 3.6% of the total $PM_{2.5}$ mass. However, because data for this CMB analysis were only available for a limited number of days, we have less confidence in this finding than in the data analysis findings for Question 1 above.

Question 3: Was the 2008/2009 wood burning season representative of normal $PM_{2.5}$ concentrations?

Answer:

Data analysis results show that the 2008/2009 winter season represented an average year, with 20 days exceeding the NAAQS. Without curtailment, the 2008/2009 winter season would have had an estimated 33 days exceeding NAAQS.

Question 4: What should the no-burn threshold be to most effectively reduce $PM_{2.5}$ below the NAAQS?

Answer:

Calculations show that to help reduce $PM_{2.5}$ below the NAAQS, the no-burn thresholds should be set as follows:

1. Single-stage program – 31 $\mu g/m^3$.
2. Two-stage program – 31 $\mu g/m^3$ for Stage 1 and 35 $\mu g/m^3$ for Stage 2.

These thresholds include a margin of safety equal to the median forecast bias for days on which (a) burning was discouraged and (b) the concentrations were under predicted.

Question 5: Should no-burn days be called on the day prior to forecasted high $PM_{2.5}$ concentration days to help lower pollution during $PM_{2.5}$ episodes?

Answer:

Modeling analysis results show that the average contribution of carryover from the prior (build-up) day to the average 24-hr $PM_{2.5}$ concentration on a “Stage” day was 0.7 $\mu g/m^3$, or 2.2% of the total observed $PM_{2.5}$ concentration. The range of contributions of carryover for

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[5] Due to the nature of CMB analysis, it is not possible to attribute secondary $PM_{2.5}$ (organic carbon and ammonium nitrate) to wood smoke emissions, even though wood smoke contributes to the formation of secondary $PM_{2.5}$. Therefore, 9.4 $\mu g/m^3$, or 25%, is likely a low-end estimate of the wood smoke contribution to total $PM_{2.5}$ concentrations.

days investigate was 0.0 to 2.7 μg/m^3, or 0 to 10.6%. Therefore, at this time, there is insufficient evidence that a no-burn day called on the day prior to high $PM_{2.5}$ concentration days will significantly lower pollution during $PM_{2.5}$ episodes.

3. METHODS

STI performed cluster analysis, CMB modeling, and numerical modeling to address the questions listed in Section 2. This section discusses the methods used to perform each of these analyses and is organized according to the question(s) addressed by each analysis.

3.1 PROGRAM EFFECTIVENESS

This subsection describes the methods used to answer the question: **What is the overall effectiveness of Rule 421 toward meeting the $PM_{2.5}$ 24-hr National Ambient Air Quality Standard (NAAQS)?**

To address this question, STI compared wintertime $PM_{2.5}$ concentrations on selected days prior to the adoption of Rule 421 (i.e., days when no restrictions on burning were in effect from November 1, 2004, through November 30, 2007) to days when Rule 421 was in effect (i.e., a Stage 1 or Stage 2 burn ban was issued). Only recent years' data were used in the analysis to limit the influence of emission changes on $PM_{2.5}$ concentrations due to non-woodburning emission control measures and population changes. $PM_{2.5}$ concentrations were only compared on days when meteorological conditions were similar; thus, the difference in $PM_{2.5}$ concentrations between days could be primarily[6] attributed to a Stage 1 or Stage 2 burn ban.

To identify days with similar meteorology, STI performed cluster analysis. Cluster analysis involves grouping like objects (in this case, days) into clusters based on the similarity of the objects' characteristics (in this case, meteorology). For this analysis, the similarity (or variation) between days was determined by calculating the Euclidean distance using the normalized values of meteorological variables such as wind speed, temperature, etc. Euclidean distance is the sum of root mean square differences of each variable between days or clusters. The statistical technique used in the cluster analysis was "K-means". K-means clustering splits a set of days into a selected number of clusters by maximizing the between-cluster variation and minimizing the within-cluster variation of the meteorological variables.

The data considered for use in the cluster analysis included 19 surface meteorological parameters and 40 upper-air meteorological parameters derived from hourly data collected at the Sacramento Executive Airport and twice-daily radiosonde data from Metropolitan Oakland International Airport. Of these 59 meteorological variables, only 12 were determined critical for differentiating day types (see **Table 3-1**). Therefore, data for these 12 meteorological variables collected on winter days (November 1 through the end of February) for 2004 through 2009 were ultimately used in the cluster analysis.

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[6] Other factors that may cause differences in $PM_{2.5}$ concentrations include, but are not limited to, changes in population, changes in emissions from non-woodburning sources such as transportation due to fleet turnover, and changes in the $PM_{2.5}$ monitoring techniques.

Table 3-1. The 12 meteorological variables used in the cluster analysis.

Maximum surface temperature (°C)
Minimum surface temperature (°C)
Average surface dew point temperature (°C)
Average daytime cloud cover
Average overnight cloud cover
Precipitation (inches)
6 a.m. – 6 p.m. PST vector averaged wind speed (knots)
6 a.m. – 6 p.m. PST vector averaged wind direction (°)
4 a.m. PST 500-mb heights (m-agl)
4 a.m. PST 700-mb relative humidity (%)
4 a.m. PST 850-mb temperature (°C)
4 a.m. PST 925-mb temperature (°C)

Once the cluster analysis was complete, STI meteorologists reviewed the results to further refine the day matches and ensure that the matched days were very similar meteorologically. This step was critical because small differences in meteorology can have a moderate impact on $PM_{2.5}$ concentrations. In particular, meteorologists reviewed the point measurements of the variables in Table 3-1 for each day and the large-scale weather patterns over the western United States at the surface and at the 500-mb pressure level of the atmosphere (~18,000 ft). Reviewing large-scale weather patterns, the meteorologist looked for and noted the similarity of the following features between matching days:

- location of surface high-pressure systems;
- orientation and strength of the surface pressure gradient;
- 500-mb height patterns (e.g., ridges of high-pressure, troughs of low pressures); and
- any other features of interest (e.g., a thermal trough on the California coast).

Table 3-2 illustrates an example of the meteorological conditions for a matching day pair which includes a “no-restriction” day (December 2, 2006) and a “Stage 2” day (January 11, 2009). **Figure 3-1** shows the surface and 500-mb weather charts for these days. Figure 3-1 and the data in Table 3-2 indicate that these days were meteorologically similar, that is, most all weather parameters important to $PM_{2.5}$ concentrations were similar on both days. Following are examples of comparisons of meteorological parameters between days: (1) the maximum surface temperatures were 15°C and 16°C on the no-restriction and Stage 2 days, respectively, while the 6 a.m. to 6 p.m. PST vector-averaged wind speeds were 0 knots on both days and (2) a ridge of high pressure at 500-mb, a thermal trough of low pressure on the California coast, and a northwest to southeast-orientated pressure gradient of similar strength (shown in Figure 3-1) occurred on both days. As a result of these meteorological similarities, differences in $PM_{2.5}$ concentrations between these two days can be attributed primarily to the burn ban.

The meteorologists also evaluated the prior-day 24-hr average $PM_{2.5}$ concentrations when selecting days for comparison. For example, if a “no-restriction” day and a “Stage 1” day were meteorologically very similar, yet the prior-day $PM_{2.5}$ concentrations were very different (i.e., difference greater than ~15 µg/m^3), then the day pair was eliminated from the day matches.

The cluster analysis and subsequent subjective review resulted in 11 matching days (day pairs). The matching days are shown in **Table 3-3**. Each day pair consisted of two days with similar meteorology: one day on which a Stage 1 or Stage 2 burn ban was called and a second day for which there were no burning restrictions. The $PM_{2.5}$ concentration data were compared for each day pair using $PM_{2.5}$ data from the site within the urban core of Sacramento County with the highest 24-hr average concentration and with data available for both days in the day-pair. For all day-pairs except one, the data collected at Del Paso Manor (DPM) were used; T Street data were used for the January 11, 2007/November 27, 2008 day-pair. For all dates except two, the data used were collected by beta attenuation monitors (BAM). Because BAM data were missing, Federal Reference Monitor (FRM) data collected at DPM were used for December 2, 2006, and December 11, 2008. The BAM and FRM data were obtained from EPA's Air Quality System (AQS) (www.epa.gov/ttn/airs/airsaqs/). Because FRM data were not available on January 11, 2009, for the December 2, 2006/January 11, 2009 day-pair, FRM data were compared to BAM data.

Table 3-2. Meteorological conditions for a matching day-pair: December 2, 2006, a no-restriction day, and January 11, 2009, a Stage 2 day.

	Del Paso Manor on Saturday, Dec 02, 2006 – No Restrictions	Del Paso Manor on Sunday, Jan 11, 2009 – Stage 2
Meteorologic Cluster	1	1
Location of surface high pressure system	Oregon	Oregon
Orientation of surface pressure gradient	Northwest-Southeast	Northwest-Southeast
Strength of surface pressure gradient	Moderate	Moderate
Surface feature of interest	Thermal trough on coast	Thermal trough on coast
500-mb pattern	Ridge	Ridge
Maximum surface temperature (°C)	15	16
Minimum surface temperature (°C)	-2	-2
Average surface dew point temperature (°C)	1	2
Average daytime cloud cover	0	1
Average overnight cloud cover	0	0
Precipitation (inches)	0	0
6 a.m. – 6 p.m. PST vector averaged wind speed (knots)	0	0
6 a.m. – 6 p.m. PST vector averaged wind direction (°)	0	72
4 a.m. PST 500-mb heights (m-agl)	5766	5887
4 a.m. PST 700-mb relative humidity (%)	8	3
4 a.m. PST 850-mb temperature (°C)	12	14
4 a.m. PST 925-mb temperature (°C)	13	15

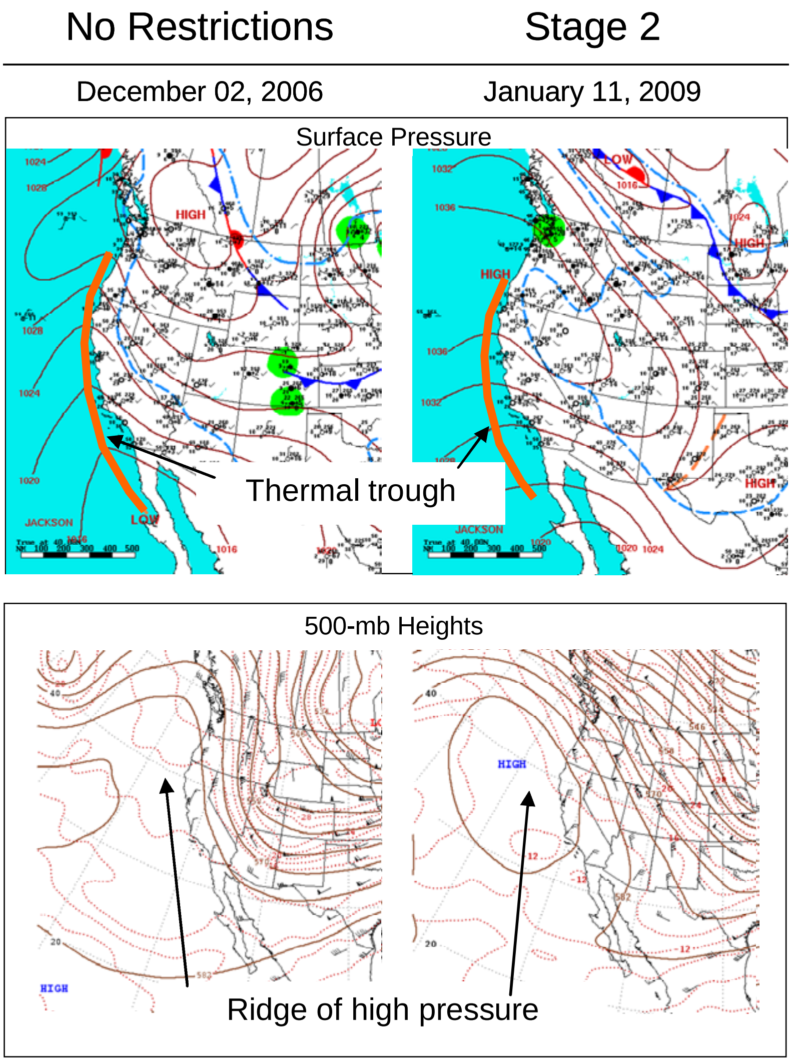

Figure 3-1. Example of surface and 500-mb weather patterns used to determine matching day-pairs. December 2, 2006, was a no-restriction day and January 11, 2009 was a Stage 2 day.

Table 3-3. Matching days when meteorological conditions were similar[7].

No Restrictions Dates	Burn Ban Dates	Stage Value
November 25, 2007	November 28, 2008	2
November 25, 2007	February 17, 2008	1
December 2, 2006	January 11, 2009	2
December 2, 2006	December 11, 2008	2
February 3, 2005	January 30, 2009	2
February 3, 2005	January 14, 2009	2
December 22, 2004	January 29, 2009	1
December 30, 2006	December 14, 2007	1
November 19, 2005	November 30, 2008	1
February 2, 2005	January 13, 2009	2
January 11, 2006	November 27, 2008	2

For the 11 day-pairs, the $PM_{2.5}$ concentration differences between the no-restriction and Stage 1 or Stage 2 days were determined for the following averaging times:

- 24-hr (12 a.m. to 12 a.m. PST);
- prior-day 24-hr (12 a.m. to 12 a.m. PST);
- morning (12 a.m. to 9 a.m. PST);
- daytime (10 a.m. to 4 p.m. PST); and
- evening (5 p.m. to 11 p.m. PST).

In addition, we compared the daily 24-hr average $PM_{2.5}$ concentrations on the days listed in Table 3-3 to concentrations on the day prior to each of these dates and calculated the concentration change between the consecutive days. We then compared the change in concentration for burn-ban days with the amount of change in concentration for their respective no-restriction dates. The purpose of this analysis was to determine how a burn ban affects the change in concentration from the day prior to a burn-ban day.

STI used the 24-hr daily average $PM_{2.5}$ concentration differences between the no-restriction and Stage 1 or Stage 2 days to estimate $PM_{2.5}$ concentrations in 2008/2009 for a no burn-ban scenario. The results were used to estimate the number of days that would have exceeded NAAQS if there was no "Check Before You Burn" (CBYB) program. This method is detailed in Section 3.3.

The results of this analysis provide an estimate of benefit from Rule 421. For example, **Table 3-4** shows the $PM_{2.5}$ concentrations for December 22, 2004, and January 29, 2009**.** The

[7] Different no-burn stages were called on November 28, 2008, and February 17, 2008, yet the days are compared to the same no-restriction day because the no-burn stages are based on forecasted meteorology; whereas, the day-pairs are based on observed meteorology.

most important column is column 4, "No Restriction minus Stage 1", a measure of the reduction in $PM_{2.5}$ concentrations resulting from the Stage 1 burn ban. In this example, the total reduction in the 24-hr average $PM_{2.5}$ concentrations resulting from the Stage 1 burn ban was 11 µg/m^3, with a maximum reduction of 43 µg/m^3 occurring during evening hours. After completing this analysis for each day pair, STI averaged the results for each averaging period listed in bullets on the preceding page.

Table 3-4. $PM_{2.5}$ concentrations comparisons for a day-pair: December 22, 2004, a no-restrictions day, and January 29, 2009, a Stage 1 day.

	Del Paso Manor on Wednesday, Dec 22, 2004 – No Restrictions	Del Paso Manor on Thursday, Jan 29, 2009 – Stage 1	**No Restrictions Minus Stage 1**
24-hr (12 a.m. – 11 p.m. PST) average $PM_{2.5}$ concentrations (µg/m^3)	40	29	**11**
Morning (12 a.m. – 9 a.m. PST) average $PM_{2.5}$ concentrations (µg/m^3)	26	31	**-5**
Daytime (10 a.m. – 4 p.m. PST) average $PM_{2.5}$ concentrations (µg/m^3)	21	21	**0**
Evening (5 p.m. – 11 p.m. PST) average $PM_{2.5}$ concentrations (µg/m^3)	77	34	**43**
Prior-day 24-hr (12 a.m. – 11 p.m. PST) average $PM_{2.5}$ concentrations (µg/m^3)	16	22	**-5**
Concentration change from the prior day (µg/m^3)	23	7	**16**

3.2 CMB MODELING

The methods used to answer the questions that follow are discussed in this subsection. The following question (in boldface) was the main focus of the analyses; important secondary questions related to these analyses are italicized.

Does CMB modeling confirm the effectiveness findings from Question 1?

How variable is the wood smoke contribution based on the various wood burning profiles?

How well does CMB predict the wood smoke contribution?

STI applied CMB modeling to speciated $PM_{2.5}$ data to determine the contribution of residential wood smoke to total $PM_{2.5}$ concentrations for various groups of days and compared the findings to the "effectiveness" findings described in Section 3.1. The day groups included

- all 2008-2009 "winter" days;
- all Stage 1 and Stage 2 days in 2007-2009;
- Stage 1 days that were matched to days with no burning restrictions because of similar meteorology between matched days;

- Stage 2 days that were matched to days with no burning restrictions because of similar meteorology between matched days; and
- no-restriction days (i.e., no burn ban was issued) that were matched to Stage 1 and Stage 2 days because of similar meteorology between matched days.

Days with similar meteorological conditions (i.e., matching days) were determined using the cluster analysis results described in Section 3.1. However, the criteria for the selection of meteorologically similar days included in the CMB modeling were less restrictive than the criteria used in the data analysis described in Section 3.1. We were less restrictive because the number days for which speciated ambient data were available for comparison were limited. The result of less restriction is that the meteorology was only moderately similar between matching days; thus, differences in wood smoke contributions between matching days cannot solely be attributed to a burn ban. The no-restriction days were selected from winter days during November 2007 through February 2009 when no burn ban was in effect, as well as from the winters prior to the CBYB program (November 2003 through February 2007). The final set of matching no-restriction days and Stage days used to compare the contribution of wood smoke are discussed in Section 4.2.

The data used for CMB modeling were validated, speciated 24-hr samples of $PM_{2.5}$ data collected at Del Paso Manor. The data were collected every third day. Ambient concentrations and uncertainty values were obtained from SMAQMD for the 2008-2009 "winter" (November 2008–February 2009) and from EPA's Air Quality System (AQS) for previous "winters" (2003–2008). The source profiles used in CMB modeling were obtained from Katarzyna Turkiewicz from the California Air Resources Board (ARB). Wood-burning source profiles from different types of wood were used in sensitivity tests to determine the range of wood smoke contributions. Standard CMB performance metrics were used to gauge confidence in results.

3.2.1 CMB Background

CMB is a receptor model used to identify and characterize the mixture and magnitude of sources contributing to ambient pollutant concentrations. Known source profiles are linearly fit to ambient data using a least squares solution. Model outputs represent the contributions of various emission sources to the observed ambient concentrations. In CMB, only source profiles (i.e., the fraction of each species emitted from each source type), and ambient data collected at the receptor are required as model inputs. Underlying CMB assumptions include (1) accurate identification of source types and abundances (source profiles); (2) independent source compositions (i.e., abundances are unique to each profile); and (3) consistent profiles between source and receptor (i.e., no mass removal and constant emissions) and throughout the sampling period. In this analysis, these assumptions were met to a similar degree as in published literature.

3.2.2 Data Processing and Quality Assurance

Each species was blank-adjusted by subtracting the median blank mass of that species from three blanks taken during 2008-2009. After blank-adjusting mass values, total mass was reconstructed from the speciated data for comparison with the total measured mass on the filter (**Figures 3-2 and 3-3**). This comparison helps us understand how well the chemical species represent the total mass on the filter. Organic carbon was adjusted to organic matter (OM) using a factor of 1.4 to account for oxygen and hydrogen associated with the carbon (Malm et al., 2004; Turpin and Lim, 2001). The factor of 1.4 is generally viewed as a low-end factor, but was used in this analysis because it provided the best reconstruction of total mass. The unknown fractions, calculated as the difference between the reconstructed and measured totals, were typically less than 20% of the total reconstructed concentration throughout the sampling period, indicating that most of the $PM_{2.5}$ mass is well explained by the measured chemical species. Additional quality assurance included investigation of ambient data values below instrument method detection limits (MDLs) (**Table 3-5**). Species frequently below detection were generally not included in the model; if a species was relatively abundant in source profiles, such as aluminum in the soil profile, it was included. AQS-reported uncertainties were used for individual species, and an uncertainty of 5.5% was used for total mass, as reported by Research Triangle Institute in the 2008-2009 data submittal to SMAQMD.

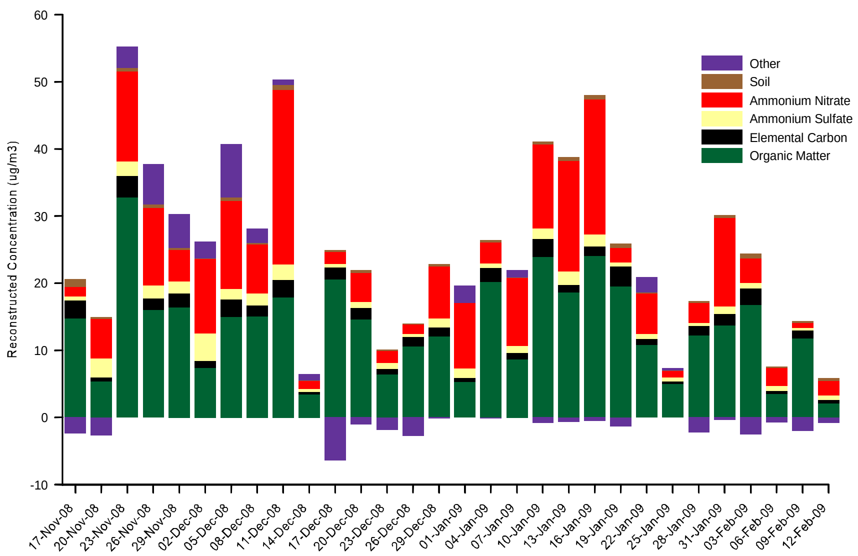

Figure 3-2. Reconstructed mass of samples during winter 2008/2009. "Other" is defined as the difference between the measured total filter mass minus the sum of soil, ammonium, nitrate, ammonium sulfate, organic matter, and elemental carbon. A negative value indicates the sum of species was greater than the measured mass.[8]

[8] Calculations were based on standard Interagency Monitoring of Protected Visual Environments (IMPROVE) methodology (IMPROVE). Soil was calculated as (Aluminum*2.2+Silicon*2.49+ Calcium*1.63 +Iron*2.42 +Titanium*1.94); ammonium nitrate was calculated as Nitrate*1.29; ammonium sulfate was calculated as Sulfur*4.125; and organic matter was calculated as Organic Carbon*1.4.

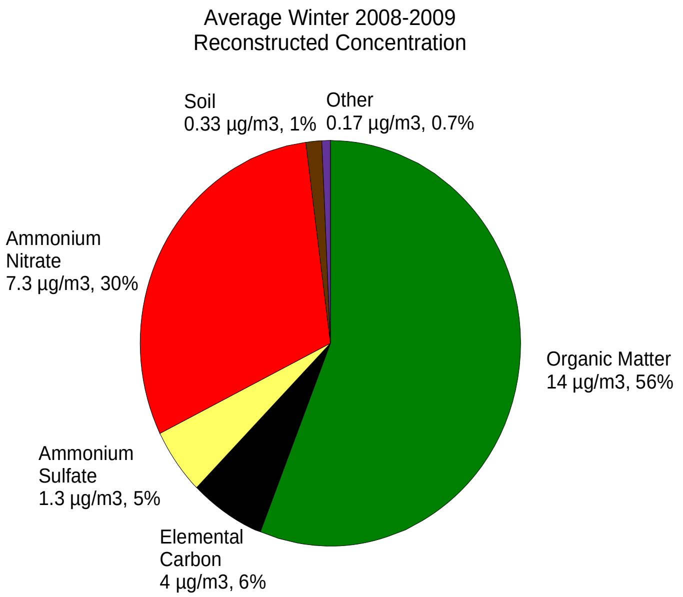

Figure 3-3. Average reconstructed concentrations plus the difference between the total reconstructed and measured concentrations (the difference is shown as “other”) for all winter 2008-2009 sample dates.

Table 3-5. Species data below method detection limits for each sample date in winter 2008-2009.

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Date	Al	NH_4	Br	Ca	Cl	Cu	EC	Fe	K	Pb	Mn	Na	Ni	NO_3	OC	K (ion)	Si	Na (ion)	SO_4	Ti	V	Zn
11/17/08					X					X		X	X								X	
11/20/08	X		X							X	X		X							X	X	
11/23/08	X										X	X	X								X	
11/26/08	X									X		X								X	X	
11/29/08	X									X	X	X	X					X		X	X	
12/02/08	X			X						X	X	X	X							X	X	
12/05/08	X										X		X							X	X	
12/08/08	X									X	X	X	X				X				X	
12/11/08	X											X	X							X	X	
12/14/08	X		X							X	X		X				X			X	X	
12/17/08	X		X	X						X	X	X	X					X		X	X	
12/20/08										X	X	X	X							X	X	
12/23/08	X					X				X	X		X				X			X	X	X
12/26/08	X									X	X		X				X			X	X	
12/29/08	X										X		X							X	X	
01/01/09	X			X						X	X	X	X				X	X		X	X	
01/04/09											X	X	X				X			X	X	
01/07/09	X			X						X	X	X	X				X			X	X	
01/10/09	X										X	X	X							X	X	

Table 3-5. Species data below method detection limits for each sample date in winter 2008-2009.

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Date	Al	NH_4	Br	Ca	Cl	Cu	EC	Fe	K	Pb	Mn	Na	Ni	NO_3	OC	K (ion)	Si	Na (ion)	SO_4	Ti	V	Zn
01/13/09											X	X	X							X	X	
01/16/09	X										X		X								X	
01/19/09	X										X	X	X					X			X	
01/22/09	X			X						X	X	X	X							X	X	
01/25/09	X			X						X	X		X							X	X	X
01/28/09	X									X	X	X	X							X	X	
01/31/09	X										X	X	X							X	X	
02/03/09	X									X		X	X							X	X	
02/06/09	X		X							X	X	X	X							X	X	X
02/09/09	X			X						X	X									X	X	
02/12/09										X	X	X								X	X	X

3.2.3 Source Profiles and Model Certainty

Source profile abundances and uncertainties were obtained from the ARB for the known major source types. The profiles included four wood smoke varieties (oak, eucalyptus, almond, and tamarisk), one combination wood smoke profile calculated as 50% oak and 50% eucalyptus, one mobile source profile (combined gas and diesel), ammonium sulfate, ammonium nitrate, pure organic carbon (OC), and dust. STI also created an additional wood smoke combination profile, calculated as one-third each oak, eucalyptus, and almond. Key species for wood burning, mobile sources, and dust are detailed in **Table 3-6.** OC, elemental carbon (EC), and potassium were used as markers for wood burning, since levoglucosan data, a more unique tracer for wood burning, were not available. We anticipate that mobile source emissions and wood burning will account for much of the OC, but there are multiple, smaller sources of OC that are not characterized, so a profile of entirely OC is used to account for these additional small sources. Ammonium sulfate and ammonium nitrate profiles are used for mass closure; these species are secondary products and so cannot be ascribed to individual sources with CMB.

The model was run for all the winter 2008-2009 sampling dates. Twenty-one species were used in the CMB model, as shown in Table 3-6. The fourteen fitting species selected in the model were abundant in the source profiles, logical markers for the predominant sources, and typically above method detection limits. The remaining seven floating species were of lesser abundance and served to validate the model and satisfy degrees of freedom requirements (Coulter, 2004). Sensitivity tests were performed to determine the range of results for each of the different wood-burning profiles. Examining these results allowed us to put bounds on the source contribution estimate for wood burning, even if a given wood profile was not wholly representative of the mix of wood burned in the area. The best performing and most reasonable wood burning profile was selected for further use, measuring model performance by three standard CMB methods:

- R square is a measure of the fraction of variance in measured concentrations that is explained by the variance in calculated concentrations. Higher R square values indicate better agreement between measured and calculated data sets; a value greater than 0.8 is considered good agreement and was required for these analyses.
- Chi square is the weighted sum of squares of the differences between calculated and measured fitting species concentrations. Lower chi square values indicate better agreement between the measured and calculated data. A chi square value less than 1 indicates very good agreement, and a chi square between 1 and 2 indicates acceptable agreement. Chi square values of less than 2 were required for these analyses.
- The total mass calculated by the model should be reasonable when compared to measured mass, falling between 80% and 120% of the measured mass. In addition, the source contribution estimates were evaluated for significance, and the ratio of calculated/measured concentrations for fitting species were compared between profiles.

Table 3-6. Chemical species included in CMB as fitting or floating species. Marker species for emission sources are highlighted in yellow. Under the column heading "Fit", cells with an "x" indicate species that were used in all CMB runs, and blank cells indicate species that were not always used because of poor fit or data below the MDL.

Species	Fit	Source
Aluminum	x	Dust
Ammonium	x	Ammonium sulfate, ammonium nitrate
Bromine	x	Gas/diesel
Calcium	x	Dust
Chlorine		Multiple
Copper	x	Gas/diesel, dust
Elemental carbon	x	Wood burning, gas/diesel
Iron	x	Dust
Potassium		Multiple
Lead		Multiple
Manganese		Multiple
Sodium		Multiple
Nickel		Multiple
Nitrate	x	Ammonium nitrate
Organic carbon	x	Wood burning, gas/diesel
Potassium (cation)	x	Wood burning
Silicon	x	Dust
Sodium (cation)		Multiple
Sulfate	x	Ammonium sulfate
Titanium	x	Multiple
Zinc	x	Multiple

3.3 SEASON REPRESENTATIVENESS

The methods used to answer the questions that follow are discussed in this subsection. The following question (in boldface) was the main focus of the analyses; an important secondary question related to these analyses is italicized.

Was the 2008/2009 wood burning season representative of normal $PM_{2.5}$ concentrations?

What would have the 2008/2009 wood burning season have been like without the CBYB program?

STI used various metrics to summarize $PM_{2.5}$ conditions for winter 2008/2009 and compared those metrics to past "winters" (2004/2005, 2005/2006, 2006/2007, and 2007/2008). Only data from recent years were used in the analysis to limit the influence of emission changes on $PM_{2.5}$ concentrations due to non-woodburning emission control measures and population changes. For this analysis, we used BAM data collected at DPM because (1) there was a complete set of data for this site for the period of interest and (2) it is typically the site with the highest daily concentrations in Sacramento County. The metrics calculated for each year included

- number of days in each Air Quality Index (AQI) category;
- number of days on which the NAAQS was exceeded; and
- average episode length. An episode is defined as one or more consecutive days exceeding the NAAQS.

STI also compared the number of days in 2008/2009 when meteorological conditions were conducive to high $PM_{2.5}$ concentrations to the number of such days in each of the prior four years. This comparison was made by reviewing the meteorological conditions and observed air quality concentrations on all winter days from November 2004 through February 2009. Conducive conditions include

- surface high pressure north or east of Sacramento;
- aloft high pressure over California;
- relatively warm aloft temperatures and a temperature inversion;
- cool and cloud-free nights; and
- light winds during the day and night.

When comparing these conditions to observed air quality, we determined that observed air quality concentrations were the best metric to define days when meteorology was conducive to poor air quality. In particular, we defined meteorologically conducive days as days when peak 24-hr average $PM_{2.5}$ concentrations exceeded 24 $\mu g/m^3$. We also reviewed the number of days above 29 $\mu g/m^3$ to confirm that our choice of threshold did not significantly change the relative difference in days with conducive meteorology between years.

Finally, STI used the burn-benefit results from the Question 1 analysis to estimate $PM_{2.5}$ concentrations in 2008/2009 had no CBYB program been in place. This estimate was calculated by adding the average Stage 1 burn-ban benefit to the observed concentrations on Stage 1 days and the average Stage 2 burn-ban benefit to the observed concentrations on Stage 2 days. The observed concentrations were adjusted using data collected using BAM monitors. STI then recalculated the metrics for the 2007/2008 and 2008/2009 seasons using the adjusted data. Of particular focus was the reduction in the number of days exceeding NAAQS due to the CBYB program.

3.4 NO-BURN THRESHOLDS

This subsection describes the methods used to answer the question: **What should the no-burn threshold be to reduce $PM_{2.5}$ below NAAQS?**

To address this question for the single-stage program, STI estimated the median bias in the daily $PM_{2.5}$ forecasts and subtracted it from the NAAQS threshold to determine the burn-ban threshold. This calculation was necessary because, in practice, if a $PM_{2.5}$ concentration of 30 $\mu g/m^3$ is forecast with a forecast error of 5 $\mu g/m^3$, an observed concentration of 35 $\mu g/m^3$ is possible given the forecast error. Therefore, the threshold for a no-burn call should be lowered to 30 $\mu g/m^3$ (35 minus 5).

For a two-stage program, STI determined a $PM_{2.5}$ threshold for which a Stage 1 call will not be sufficient to prevent a violation of the NAAQS. To determine this threshold, STI added the anticipated $PM_{2.5}$ reduction resulting from a Stage 1 call (obtained from the data analyses performed to address Question 1) to the NAAQS of 35 $\mu g/m^3$ and subtracted the forecast error. For example, if the average reduction achieved on a Stage 1 day is 4 $\mu g/m^3$, the no-burn threshold for a Stage 2 day (ignoring forecast error) should be 39 $\mu g/m^3$ (35 +4). If forecast error is 5 $\mu g/m^3$, the threshold for a Stage 2 no-burn call day should be lowered to 34 $\mu g/m^3$ (39-5).

The forecast error used in the these calculations was determined by calculating the median forecast bias for days during the 2008/2009 winter season when burning was discouraged. Using the forecast bias from burning-discouraged days was determined to be the most appropriate estimate of the actual forecast error for the following reasons: (1) on days when a Stage 1 or Stage 2 burn ban is called, the forecast error can be altered by the effectiveness of the burn ban; (2) on clean days, precise forecasts of absolute $PM_{2.5}$ concentrations tend to be emphasized less compared to days on which a burn ban may be necessary; and (3) on days when burning is discouraged, forecast accuracy is emphasized, yet there is no burn ban to alter forecast error.

3.5 BUILD-UP DAY RULE

This subsection describes the methods used to answer the question: **Should no-burn days be called on the day prior to forecasted high $PM_{2.5}$ concentration days to help lower pollution during $PM_{2.5}$ episodes?**

STI used the BlueSky Gateway air quality modeling system. BlueSky Gateway is an operational $PM_{2.5}$ forecasting system developed for the U.S. Forest Service to predict $PM_{2.5}$ concentrations resulting from wildfires and other emission sources on a national scale at coarse

(36 km) resolution. BlueSky Gateway combines meteorological predictions from the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) with air quality predictions from the Community Multiscale Air Quality (CMAQ) model. STI has operated BlueSky Gateway twice daily since its Summer 2007 inception.

Though BlueSky Gateway was designed primarily to track and predict $PM_{2.5}$ concentrations resulting from wildfires, the modeling system is run with full gaseous and aerosol chemistry to predict the fate of all types of natural and anthropogenic $PM_{2.5}$ emission sources, including residential wood burning. Details pertinent to the use of BlueSky Gateway to address the questions posed by SMAQMD are presented below. Additional details can be found in (Craig et al., 2007).

STI performed simulations for several two-consecutive-day periods using the BlueSky Gateway modeling system to evaluate the contribution of carryover on multi-day pollution episodes. BlueSky Gateway was run for several days prior to each case date (with residential wood burning allowed) to provide initialized concentration fields for the sensitivity simulations.

Nine cases from the 2008/2009 winter burning season were selected for this analysis, as shown in **Table 3-7**. Each case consists of a "build-up" day on which burning was discouraged, followed by a "Stage" day on which a Stage 1 or Stage 2 burn ban was called. In several instances, these cases represented the beginning of extended periods of elevated $PM_{2.5}$ concentrations that necessitated burn bans on several consecutive days in Sacramento County.

Table 3-7. Cases selected for modeling analysis.

Case	Date	Burn Category	Observed $PM_{2.5}$ ($\mu g/m^3$)
1	11/16/2008	Discouraged	30.8
	11/17/2008	Stage 1	23.8
2	11/22/2008	Discouraged	49.4
	11/23/2008	Stage 2	60.7
3	11/29/2008	Discouraged	35.6
	11/30/2008	Stage 1	42.3
4	12/2/2008	Discouraged	33.3
	12/3/2008	Stage 2	29.3
5	12/9/2008	Discouraged	34.0
	12/10/2008	Stage 2	40.5
6	1/4/2009	Discouraged	31.1
	1/5/2009	Stage 2	25.7
7	1/6/2009	Discouraged	25.5
	1/7/2009	Stage 2	29.2
8	1/9/2009	Clean	17.8
	1/10/2009	Stage 2	43.5
9	1/28/2009	Discouraged	21.6
	1/29/2009	Stage 1	28.9

For each case, STI ran the two-consecutive-day simulations for two residential wood-burning scenarios:

1. 100% burning curtailment in Sacramento County only on the Stage day.
2. 100% burning curtailment in Sacramento County on both the build-up and the Stage days.

The modeled difference in $PM_{2.5}$ concentrations between these two emission scenarios on the Stage day yields the relative benefit of adding a burn ban on the build-up day. The modeled impacts of carryover were examined at various receptor locations throughout Sacramento County.

Residential wood combustion emission estimates were taken from the 2002 National Emission Inventory (NEI), processed through version 2.3 of the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE), and projected to 2007 using growth factors generated by EPA's Economic Growth Analysis System (EGAS) version 4.0. The residential wood combustion emission estimates used in BlueSky Gateway are listed in **Table 3-8**. These estimates are within approximately 5% of the 2009 California Air Resources Board (ARB) residential wood-burning emission estimates for Sacramento County obtained from the California Emission Forecast System (CEFS) (http://www.arb.ca.gov/app/emsinv/fcemssumcat2005.php), as shown in **Table 3-9**. SMOKE speciates the total $PM_{2.5}$ mass according to the speciation profile shown in **Table 3-10** and applies temporal profiles to convert annualized emissions to episode-specific hourly emissions. The allocation of annual wood-burning emissions by month is shown in Figure 3-4. The default SMOKE seasonal profile applied to residential wood combustion emissions was judged to be reasonable and resulted in average winter day $PM_{2.5}$ emissions of 10.4 tons for Sacramento County. The default SMOKE diurnal temporal profile for residential wood combustion was replaced with a more appropriate profile developed by ARB.

Table 3-8. 2007 Sacramento County residential wood combustion emission estimates (tons/year) used in BlueSky Gateway simulations.

Source	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
Fireplaces	11,150.9	114.8	1,428.1	1,374.8	17.5	600.1
Woodstoves	1,789.9	25.3	279.8	269.4	3.8	130.8
Total	12,940.8	140.1	1,708.0	1,644.2	21.3	730.9

Table 3-9. 2009 Sacramento County residential wood combustion emission estimates (tons/year) from the CEFS database.

Source	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
Fireplaces	11,744.3	120.9	1,504.2	1,448.0	18.5	632.0
Woodstoves	1,788.3	25.5	279.6	269.1	3.7	130.5
Total	13,532.6	146.4	1,783.8	1,717.1	22.1	762.5

Table 3-10. SMOKE $PM_{2.5}$ speciation profile.

Profile #	Model Species	Model Species Name	Mass Fraction
22061	PEC	Primary elemental carbon	0.1077
22061	PMFINE	Fine mode PM (metals and other species)	0.3208
22061	PNO_3	Primary nitrate aerosol	0.0022
22061	POA	Primary organic aerosol	0.5656
22061	PSO_4	Primary sulfate aerosol	0.0037

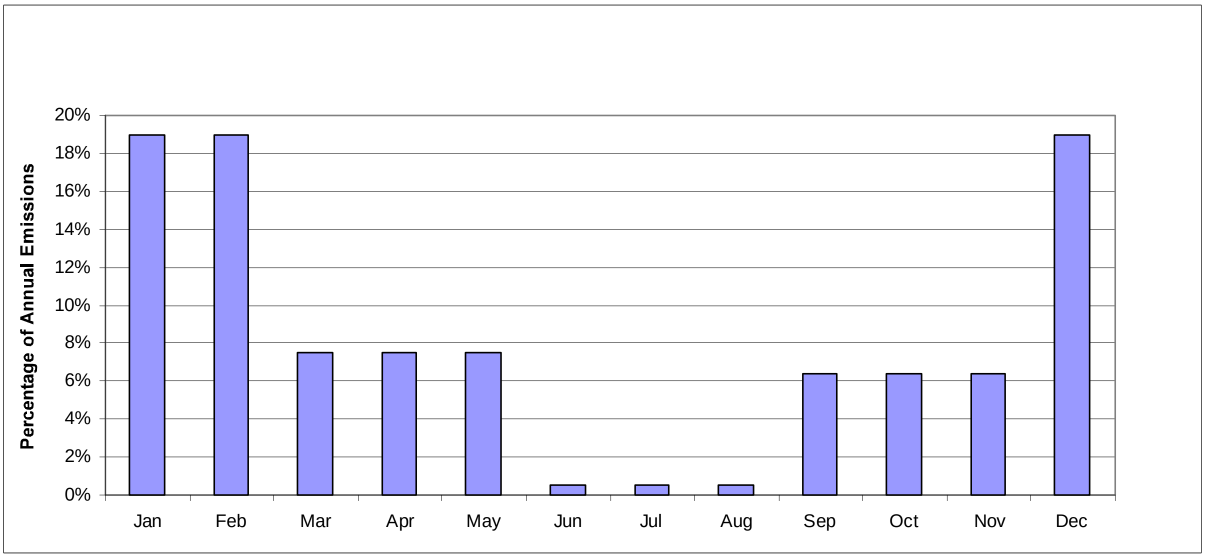

Figure 3-4. Allocation of annual wood-burning emissions by month.

Because of the relatively coarse horizontal resolution of BlueSky Gateway (36 km), peak concentrations may be underestimated by the model as localized emissions are artificially diluted into relatively large model grid cells. **Figure 3-5** illustrates the size of BlueSky Gateway model grid cells relative to Sacramento County. To address the effects of model resolution, the use of absolute modeled concentration differences was avoided, and instead the *relative* difference between the two emission control scenarios was used to determine the impact of carryover.

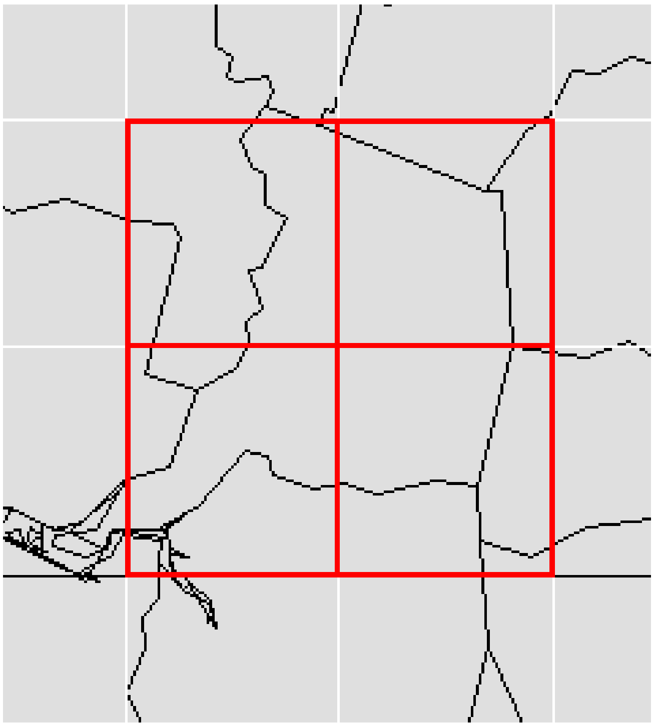

Figure 3-5. BlueSky Gateway model grid in the Sacramento County region. Grid cells highlighted in red indicate the four cells that encompass most of Sacramento County.

4. FINDINGS

Findings related to each question listed in Section 2 are summarized in this section and are organized according to the main question addressed by each analysis.

4.1 PROGRAM EFFECTIVENESS

Detailed in this subsection are the findings applicable to Question 1: **What is the effectiveness of program toward meeting NAAQS?**

STI compared wintertime $PM_{2.5}$ concentrations on days prior to the adoption of Rule 421 (i.e., no burning restrictions) to days when Rule 421 was in effect (i.e., when a Stage 1 or Stage 2 burn ban was issued). $PM_{2.5}$ concentrations were only compared for days when meteorological conditions were similar; thus, the difference in $PM_{2.5}$ concentrations between days could be primarily attributed to a Stage 1 or Stage 2 burn ban. Cluster analysis and subsequent subjective review resulted in 11 matching days (day pairs), which are shown in Table 3-3. Each day pair consists of two days with similar meteorology: one day on which a Stage 1 or Stage 2 burn ban was issued and a second day on which no burning restrictions were imposed. Overall, seven Stage 2 day pairs and four Stage 1 day pairs were identified. Because of the limited number of day pairs, the results derived from analysis should be viewed as rough approximations.

Table 4-1 lists the average reduction in $PM_{2.5}$ concentrations for various averaging periods (24-hr, morning, daytime, and evening) that resulted from a Stage 1 or Stage 2 burn ban. **Figure 4-1a** shows time series of the average hourly $PM_{2.5}$ concentrations for all Stage 2/ no-restriction day pairs. **Figure 4-1b** shows time series of the average hourly $PM_{2.5}$ concentrations for all Stage 1/no-restriction day pairs. **Table 4-2** lists the 24-hr $PM_{2.5}$ concentration reduction (benefit) for each of the 11 day-pairs. The tables and figures illustrate the following findings:

- The average reduction resulting from a Stage 1 burn ban was 4 $\mu g/m^3$, or 10% of the total $PM_{2.5}$ mass that would have occurred without the reduction. For example, if a concentration of 36 $\mu g/m^3$ was observed on a day with a Stage 1 burn ban, the concentration would have been about 40 $\mu g/m^3$ on average without a burn ban.
- The reductions resulting from a Stage 1 burn ban ranged from -11 $\mu g/m^3$ to 10 $\mu g/m^3$. A reduction was observed on three of the four days (Table 4-2**)**.
- The average reduction resulting from a Stage 2 burn ban was 12 $\mu g/m^3$, or 23% reduction of the total $PM_{2.5}$ mass that would have occurred without the reduction. For example, if a concentration of 40 $\mu g/m^3$ was observed on a day with a Stage 2 burn ban, the concentration would have been about 52 $\mu g/m^3$ on average without the Stage 2 burn ban.
- The reductions resulting from a Stage 2 burn ban ranged from -6 $\mu g/m^3$ to 30 $\mu g/m^3$. A reduction was observed on six of the seven days (Table 4-2**)**.
- The greatest reduction in $PM_{2.5}$ concentrations resulting from a burn ban occurred during the evening hours. This reduction can be seen in the large separation between the dashed red line (average "No Restriction" days) and solid green lines (average Stage 1 or Stage 2

days) in Figures 4-1a and 4-1b. The average reduction during the evening was 23 µg/m^3 and 19 µg/m^3 for Stage 2 and Stage 1 days, respectively. This result is consistent with the observation that most people burn in the evening as indicated in the ARB residential wood-burning emission estimates for Sacramento County obtained from the CEFS.

- The average change in the 24-hr daily average concentration from a day prior to a Stage 2 day was 17 µg/m^3 less than the change from a day prior to a no-restriction day (see the last row in Table 4-1). This result suggests that without a Stage 2 burn ban, concentrations would have been, on average, 17 µg/m^3 higher than without a burn ban.
- The average change in the 24-hr daily average concentration from a day prior to a Stage 1 day was 5 µg/m^3 less than the change from a day prior to a no-restriction day (see the last row in Table 4-1). This result suggests that without a Stage 1 burn ban, concentrations would have been on average 5 µg/m^3 higher than without a burn ban.

Table 4-1. Average reduction (benefit) for all day-pairs, Stage 2 day-pairs, and Stage 1 day-pairs.

	Benefit Stage 1 and 2 (µg/m^3)	Benefit Stage 2 (µg/m^3)	Benefit Stage 1 (µg/m^3)
24-hr	9	12	4
Morning	8	11	3
Daytime	-7	-4	-11
Evening	21	23	19
Change from the prior day	12	17	5

(a)

(b)

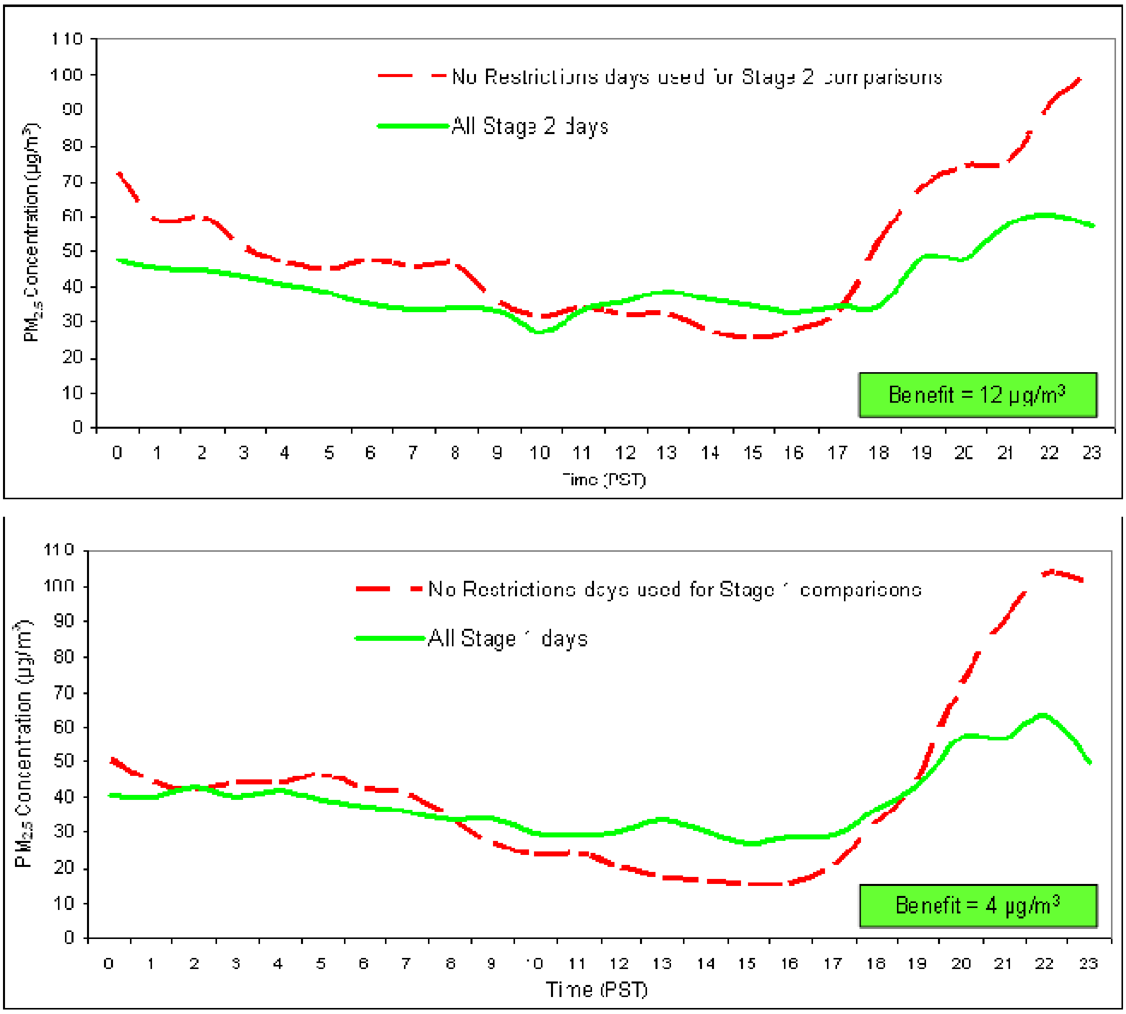

Figure 4-1. Average hourly $PM_{2.5}$ time series for the (a) Stage 2 and (b) Stage 1 day pairs. The dashed red line represents the average hourly $PM_{2.5}$ concentrations for the No Restriction days associated with each day pair, and the solid green line represents the average hourly $PM_{2.5}$ concentrations of the Stage days associated with each day pair. The green box show the estimated total reduction (benefit) in the 24-hr average $PM_{2.5}$ concentrations due to the burn ban.

Table 4-2. The 24-hour $PM_{2.5}$ concentration reduction (benefit) for each day-pair. Green cells indicate a benefit from the burn ban.

Day Pairs				
No Restrictions Date	Burn Ban Date	Burn Ban Category	24-hr Daily Average $PM_{2.5}$ Concentration Reduction ($\mu g/m^3$)	Concentration change from a "prior" day to a no-restriction day minus the concentration change from a prior "day" to a Stage day
November 25, 2007	November 28, 2008	Stage 2	15	13
November 25, 2007	February 17, 2008	Stage 1	9	3
December 2, 2006	January 11, 2009	Stage 2	23	26
December 2, 2006	December 11, 2008	Stage 2	30	30
February 3, 2005	January 30, 2009	Stage 2	6	1
February 3, 2005	January 14, 2009	Stage 2	-5	2
December 22, 2004	January 29, 2009	Stage 1	10	16
December 30, 2006	December 14, 2007	Stage 1	6	8
November 19, 2005	November 30, 2008	Stage 1	-11	-7
February 2, 2005	January 13, 2009	Stage 2	-6	12
January 11, 2006	November 27, 2008	Stage 2	18	31

4.2 CMB MODELING

The findings applicable to the questions that follow are detailed in this subsection. The following question (in boldface) was the main focus of the analyses; important secondary questions related to these analyses are italicized.

Does CMB modeling confirm the effectiveness findings?

How variable is the wood smoke contribution based on the various wood-burning profiles?

How well does CMB predict the wood smoke contribution?

Figure 4-2a-e shows the average source contributions to total $PM_{2.5}$ concentration at Del Paso Manor for five day-groupings. The wood smoke contribution and other observations derived from these figures are noted below.

1. Figure 4-2a shows that, on all 2008-2009 winter days, the average wood smoke contribution was 7.1 $\mu g/m^3$ or 29% of the total $PM_{2.5}$ mass. Thus, if wood burning were reduced to negligible levels, the burn ban could produce concentration reductions of this magnitude. This finding supports the estimated reduction in $PM_{2.5}$ concentrations resulting from burn bans described in Section 4.1 regarding Question 1.

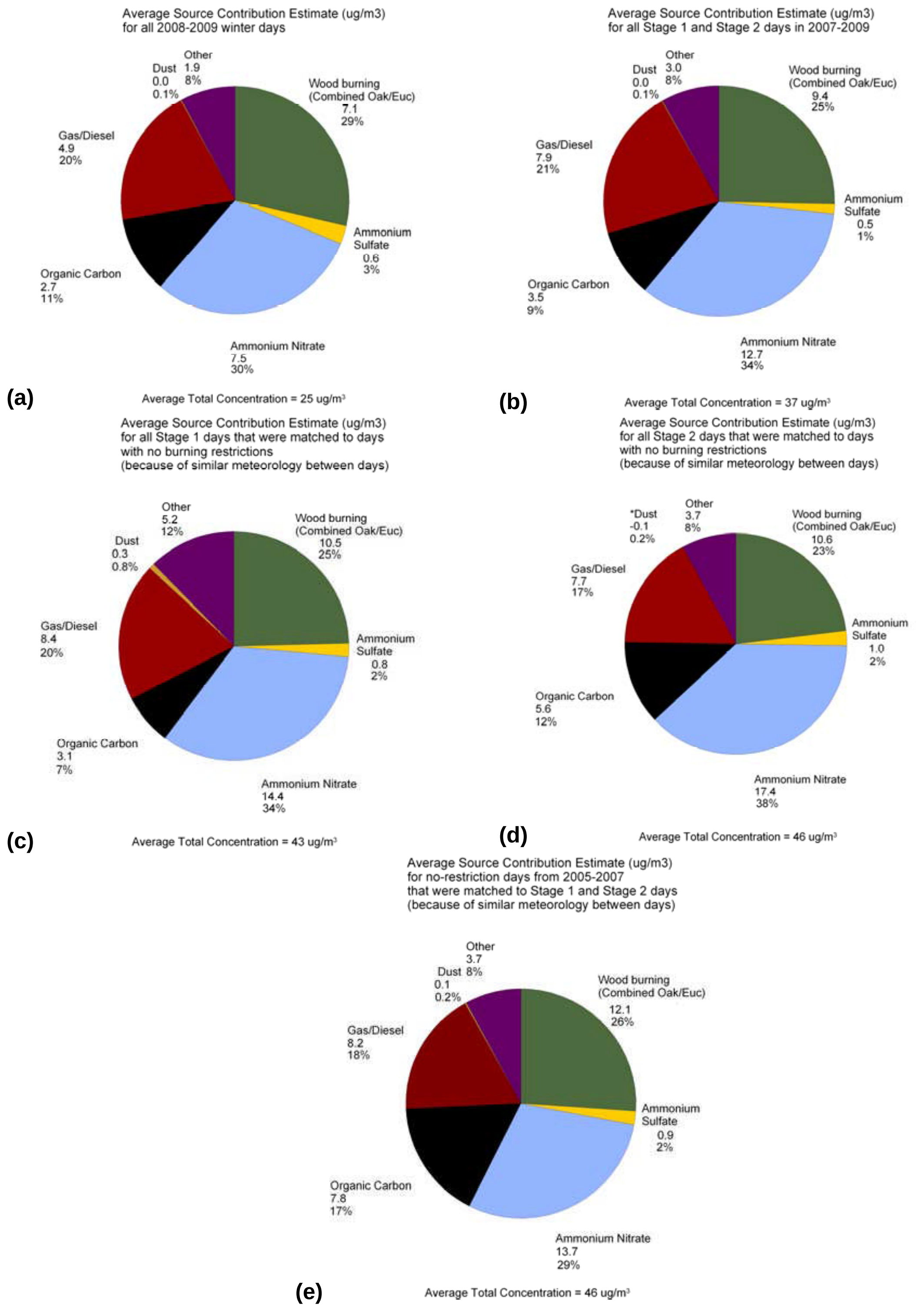

Figure 4-2. Source contribution estimates for each profile averaged across (a) all winter 2008-2009 sample dates, (b) all 2008/2009 Stage dates, (c) Stage 1 days with matching no-restriction days, (d) Stage 2 days with matching no-restriction days, (e) no-restriction days with meteorology similar to Stage days.

2. Figure 4-2b shows that, on all 2007/2009 Stage 1 and Stage 2 days, the average wood smoke contribution was 9.4 µg/m^3 or 25% of the total $PM_{2.5}$ mass.
3. Figure 4-2c shows that, on Stage 1 days that were matched to days with no burning restrictions because of similar meteorology, the average wood smoke contribution was 10.5 µg/m^3 or 25% of the total $PM_{2.5}$ mass.
4. Figure 4-2d shows that, on Stage 2 days that were matched to days with no burning restrictions because of similar meteorology, the average wood smoke contribution was 10.6 µg/m^3 or 23% of the total $PM_{2.5}$ mass.
5. Figure 4-2e shows that, on no-restriction days from 2005 – 2007 (i.e., no burn ban was issued) that were matched to Stage 1 and Stage 2 days because of similar meteorology, the average wood smoke contribution was 12.1 µg/m^3 or 26% of the total $PM_{2.5}$ mass.

The combination of the findings 3 through 5 suggest that CMB modeling indicates a reduction of $PM_{2.5}$ from a Stage 1 or Stage 2 burn is about 1.5 µg/m^3 (12.1 – 10.5). This amount is much less than that revealed in the data analysis (see Section 4.1) and is probably not a significant enough difference to conclude that there was a benefit from burn bans. However, because data for only a limited number of days were available for this CMB analysis, the matching pairs of no-restriction to burn-ban days were not as meteorologically similar as those used in the data analysis. Therefore, differences in meteorology between days may account for the limited reduction in $PM_{2.5}$ concentrations resulting from burn bans identified using CMB.

Table 4-3 shows the reduction in wood smoke contributions for each matching pair of no-restriction to burn-ban days. Of note, the only cluster having several meteorologically similar dates for comparison, including five unrestricted dates and four Stage dates, showed a 4.0 µg/m^3 reduction for burn-ban days compared to no-restriction days. In addition, the maximum contribution of wood smoke for this cluster of days was 40% or 18.8 µg/m^3 of the total $PM_{2.5}$ concentration and occurred December 4, 2006.

In the Sacramento County emission inventory, residential wood burning accounts for approximately 50% of the primary $PM_{2.5}$ emissions. This percentage is consistent with CMB results. Ammonium nitrate and ammonium sulfate are secondarily produced and are not included in the emission inventory estimate. If these species are ignored in Figure 4-2, wood burning would account for approximately 50% of the remaining mass.

Secondary Question 1: How variable is the wood smoke contribution based on the various wood-burning profiles?

Three wood-burning source profiles were evaluated to determine the most appropriate burning profile for Sacramento County. The estimated wood smoke contribution to total calculated concentration was consistent among the three wood-burning profiles (oak, eucalyptus, and almond) and the two combination profiles. Source contribution estimates for the almond, oak, eucalyptus, and combined profiles varied between 4% and 8% (**Figure 4-3**). Variability was the greatest on Stage 2 and unrestricted dates. The consistency among the results using the oak, eucalyptus and almond profiles promotes confidence in the overall performance of CMB modeling in quantifying wood burning. As anticipated, the results when using the Tamarisk profile (tamarisk is a type of grass) were unrealistic, and the model performance was poor. The average wood smoke contribution was 82%, and the average measured mass calculated by the model was 139%, measurably exceeding the 120% threshold. This profile represents grassland burning, so if results had been good for wintertime data, the data or profiles being used would be suspect, but since the results were poor, we have more confidence in the other burning profiles and results.

Table 4-3. Reduction in wood smoke contributions for the cluster sample dates.

Meteorological Cluster	Date (Stage Level)	Wood Smoke Contribution	
		Percent	Concentration (µg/m^3)
1	2/3/2005	16	7.8
1	12/4/2006	40	18.8
1	1/9/2007	37	16.7
1	1/24/2007	32	17.3
1	2/2/2007	23	10.9
1	1/19/2008 (1)	27	11.9
1	12/11/2008 (2)	21	10.0
1	1/10/2009 (2)	32	11.9
1	1/13/2009 (2)	20	7.3
Average	Non-Stage	29	14.3
	Stage (1 or 2)	25	10.3
Reduction			4.0
3	11/21/2005	33	12.3
3	2/5/2007	26	8.6
3	11/23/2008 (2)	29	13.3
Average	Non-Stage	29	10.5
	Stage (1 or 2)	29	13.3
Reduction			-2.8
6	12/15/2005	18	5.3
6	12/5/2008 (1)	30	10.0
Reduction			-4.7
7	1/18/2007	35	17.5
7	12/14/2007 (1)	28	12.1
Reduction			5.4
9	1/11/2006	17	5.8
9	11/26/2008 (1)	27	8.1
Reduction			-2.3
All Clusters			
Average	Non-stage	28	12.1
	Stage (1)	28	10.5
	Stage (2)	25	10.6
	Stage (1 or 2)	27	10.6
Reduction			1.5

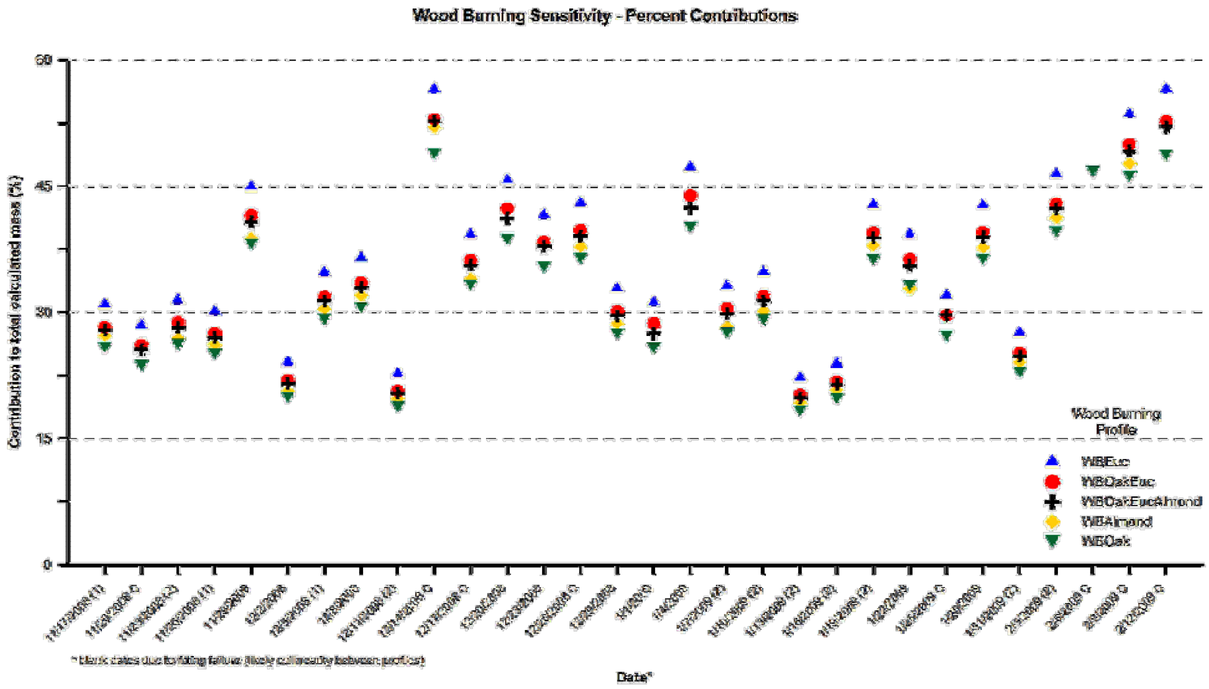

Figure 4-3. Percent of contributions to total calculated concentrations for the eucalyptus, oak, almond, and combined wood-burning source profile.

Secondary Question 2: How well is CMB at predicting the contribution?

Three metrics were used to assess the certainty in CMB model predictions: R-square, chi square, and a comparison of the total mass calculated by the model and measured mass. Overall, CMB prediction statistics were within tolerances so comparison of source contributions among days is reasonable (**Table 4-4**). In addition, using profiles of almond, eucalyptus, oak, oak and eucalyptus combined, and oak, almond, and eucalyptus combined provided a similar estimate of the contribution of wood smoke to total $PM_{2.5}$ mass (**Table 4-5**).

The combined oak and eucalyptus profile performed very well in the CMB analysis. On all but two sample dates the R square values were greater than 0.8, indicating variance in the data was explained well by the model. The two exceptions were unrestricted burn dates, for which total measured concentrations were low (less than 10 µg/m^3), where poorer model performance is expected. Only three samples exceeded the chi square performance metric on dates with substantial mass (approximately 20 µg/m^3 or greater). The model was unable to identify at least 80% of the measured mass on only two dates, November 26 and November 29, which had concentrations in excess of 35 µg/m3. However, on these dates the total concentrations reconstructed from ambient speciated data were also much less than the measured concentrations, so we expect the model calculated mass to be relatively low. Performance was also gauged using the ratio of the calculated to measured concentration for each fitting species. Ratios substantially greater than 1 were selectively not included as fitting species for certain sample dates. The ratio for EC was typically between 1 and 2. The CMB calculations could be improved by using levoglucosan data to provide a more unique tracer.

Table 4-4. Performance metrics for the combined oak/eucalyptus wood-burning profile. Red indicates Stage 2 days, orange indicates Stage 1 days, clear indicates burning discouraged days, green indicates burn cleanly days, and yellow indicates fitting statistics outside of criteria.

Date	Observed Concentration (μg/m^3)	Reconstructed Concentration (μg/m^3)	R Square	Chi Square	Percent of Measured Mass
11/17/2008	18.3	17.9	0.89	1.36	98
11/20/2008	12.3	14.4	0.97	1.10	118
11/23/2008	55.3	46.3	0.98	0.74	84
11/26/2008	37.7	29.9	0.96	1.23	79
11/29/2008	30.3	23.3	0.98	0.62	77
12/2/2008	26.3	23.3	0.97	1.16	89
12/5/2008	40.7	32.9	0.97	1.43	81
12/8/2008	28.1	24.4	0.94	1.76	87
12/11/2008	50.3	48.6	0.96	0.95	97
12/14/2008	6.4	5.2	0.74	6.60	82
12/17/2008	18.5	21.1	0.98	0.79	114
12/20/2008	20.9	20.1	0.96	1.50	96
12/23/2008	8.3	8.8	0.95	1.34	107
12/26/2008	11.3	12.3	0.91	2.17	109
12/29/2008	22.6	21.4	0.96	1.01	95
1/1/2009	19.6	17.2	0.91	3.50	88
1/4/2009	26.3	22.9	0.97	0.96	87
1/7/2009	21.9	20.7	0.93	3.09	94
1/10/2009	40.3	37.3	0.96	1.00	93
1/13/2009	38.1	37.1	0.93	2.76	97
1/16/2009	47.5	45.1	0.94	1.75	95
1/19/2009	24.6	22.8	0.90	1.70	93
1/22/2009	20.9	17.1	0.96	1.30	82
1/25/2009	7.3	5.9	0.78	7.06	80
1/28/2009	15.2	15.5	0.95	1.21	102
1/31/2009	29.8	28.2	0.95	1.36	95
2/3/2009	21.9	22.6	0.92	1.36	103
2/9/2009	12.4	12.9	0.91	1.77	104
2/12/2009	5.1	6.7	0.89	2.77	132

Table 4-5. Percent of wood smoke contributions to total calculated mass for each wood-burning profile. Red indicates Stage 2 days, orange indicates Stage 1 days, clear indicates burning discouraged days, and green indicates burn cleanly days. Burn cleanly days are days with no burning restrictions and concentrations were less than 25 µg/m^3. Due to collinearity between sources, some days were unable to be fit by the model (blank percent contribution).

		Percent Contribution (%)					
Date	Total $PM_{2.5}$ Concentration (µg/m^3)	Almond	Eucalyptus	Oak	Oak and Eucalyptus	Oak, Almond, and Eucalyptus	Tamarisk
11/17/2008	18.3	27	31	26	28	28	
11/20/2008	12.3		29	24	26	26	67
11/23/2008	55.3	27	31	26	29	28	73
11/26/2008	37.7	26	30	25	28	27	71
11/29/2008	30.3	39	45	38	42	41	92
12/2/2008	26.3	21	24	20	22	22	58
12/5/2008	40.7	30	35	29	32	31	76
12/8/2008	28.1	32	37	31	34	33	83
12/11/2008	50.3	20	23	19	21	20	50
12/14/2008	6.4	52	57	49	53	53	109
12/17/2008	18.5	34	39	33	36	36	86
12/20/2008	20.9		46	39	42	41	95
12/23/2008	8.3		42	35	38	38	85
12/26/2008	11.3	38	43	36	40	39	91
12/29/2008	22.6	29	33	27	30	30	75
1/1/2009	19.6		31	26	29	28	72
1/4/2009	26.3		47	40	44	42	96
1/7/2009	21.9	28	33	28	30	30	77
1/10/2009	40.3	30	35	29	32	31	78
1/13/2009	38.1	19	22	18	20	20	56
1/16/2009	47.5	21	24	20	22	21	59
1/19/2009	24.6	38	43	36	39	39	91
1/22/2009	20.9	33	39	33	36	36	86
1/25/2009	7.3		32	27	30	30	74
1/28/2009	15.2	38	43	36	40	39	91
1/31/2009	29.8	24	28	23	25	25	67
2/3/2009	21.9	41	46	40	43	42	92
2/6/2009	6.8			47			103
2/9/2009	12.4	48	54	46	50	49	105
2/12/2009	5.1		57	49	53	52	111
Avg. no restriction days		43	44	39	41	41	93
Avg. Stage 1		28	32	27	29	29	73
Avg. Stage 2		28	32	27	29	29	71

4.3 SEASON REPRESENTATIVENESS

The findings applicable to the questions that follow are detailed in this subsection. The following question (in boldface) was the main focus of the analyses; an important secondary question related to these analyses is italicized.

Was the 2008/2009 wood burning season representative of normal $PM_{2.5}$ concentrations?

What would have the 2008/2009 season been like without the "Check Before You Burn" (CBYB) program?

Compared to the preceding four years, the 2008/2009 winter season represents an average year in terms of the number of days exceeding the NAAQS. According to the daily BAM measurements from DPM, there were 20 exceedance days[9] during the 2008/2009 "winter" season, compared to an average of 16 exceedances for the preceding four "winters" (2004/2005, 2005/2006, 2006/2007, and 2007/2008) (see **Figure 4-4**). In addition, 2008/2009 represents a polluted year in terms of the number of days when meteorological conditions were conducive to poor air quality and was similar to 2006/2007 in that regard (see **Figure 4-5**). When the average burn-ban benefit for Stage 1 and Stage 2 days (findings discussed in Section 4.1) was added to the observed daily concentrations on Stage 1 and Stage 2 days, the number of exceedance days in 2008/2009 increased from 20 to 33 (see Figure 4-4). Therefore, the CBYB program could have reduced the number of exceedance days during the 2008/2009 winter season by about 40% (or 13 days).

Figure 4-6 shows the distribution of peak daily (a) observed AQI and (b) estimated AQI if there was no CBYB program for the 2008/2009 season. As noted in the figure, calculations show that the CBYB program resulted in a significant reduction in the number of days with Unhealthy for Sensitive Groups and Unhealthy AQI levels.

Figure 4-7 shows the average $PM_{2.5}$ pollution episode length for the 2004/2005 through 2008/2009 winter seasons; "episode" is defined as the number of consecutive days exceeding the NAAQS. Figure 4-7 show the average episode length in 2008/2009 of about 3.3 days, the longest average episode length among winters evaluated (along with the winter of 2005/2006). When the average episode length is recalculated using the estimated number of days that $PM_{2.5}$ concentrations would have exceeded the NAAQS without the CBYB program, the 2008/2009 average episode length increases to more than 4 days (see Figure 4-7).

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[9] Official NAAQS exceedance days for non-attainment designation are based on FRM data. To be NAAQS-compliant for $PM_{2.5}$, the NAAQS can be exceeded about two days a year if samples were taken every third day, and about five days if the sampling frequency was daily.

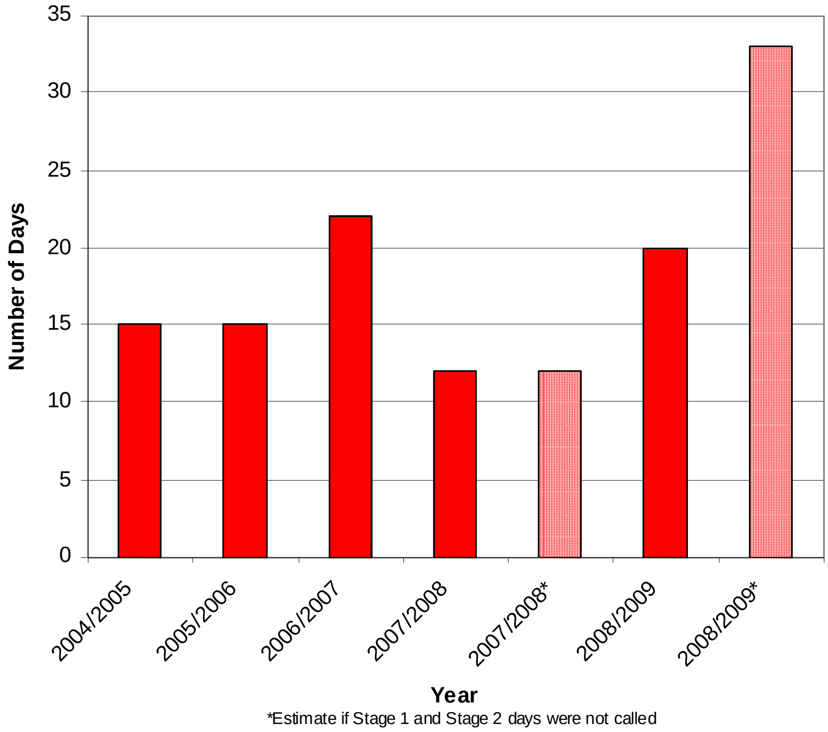

Figure 4-4. Number of days that $PM_{2.5}$ concentrations exceeded the NAAQS from the 2004/2005 through 2008/2009 winter seasons (solid bars), and estimated number of days $PM_{2.5}$ concentrations would have exceeded the NAAQS without the CBYB program (striped bars). NAAQS exceedances were determined using the daily BAM data collected at Del Paso Manor.

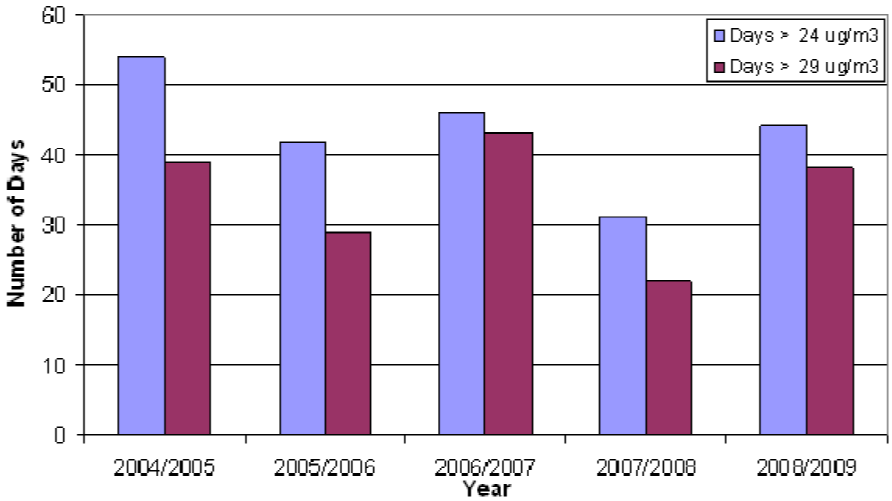

Figure 4-5. Number of meteorologically conducive days for high $PM_{2.5}$ concentrations for the 2004/2005 through 2008/2009 winter seasons.

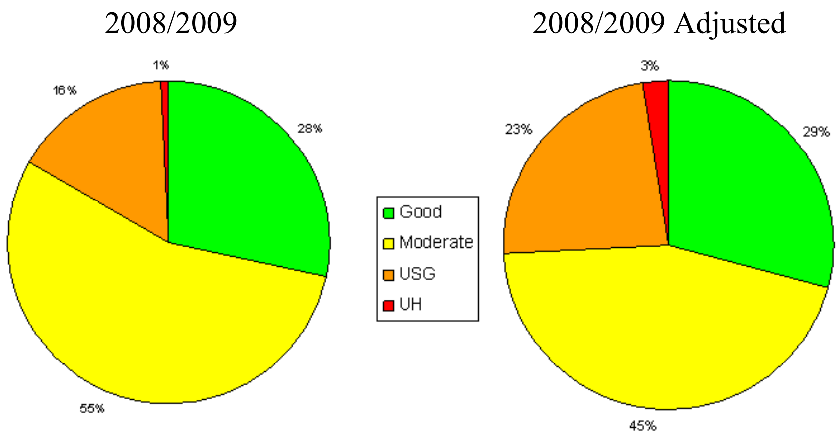

Figure 4-6. Distribution of peak daily $PM_{2.5}$ AQI by category for the 2008/2009 season observed (left) and estimated if there was no CBYB program (right). AQI categories were determined using daily BAM data from all sites within Sacramento County.

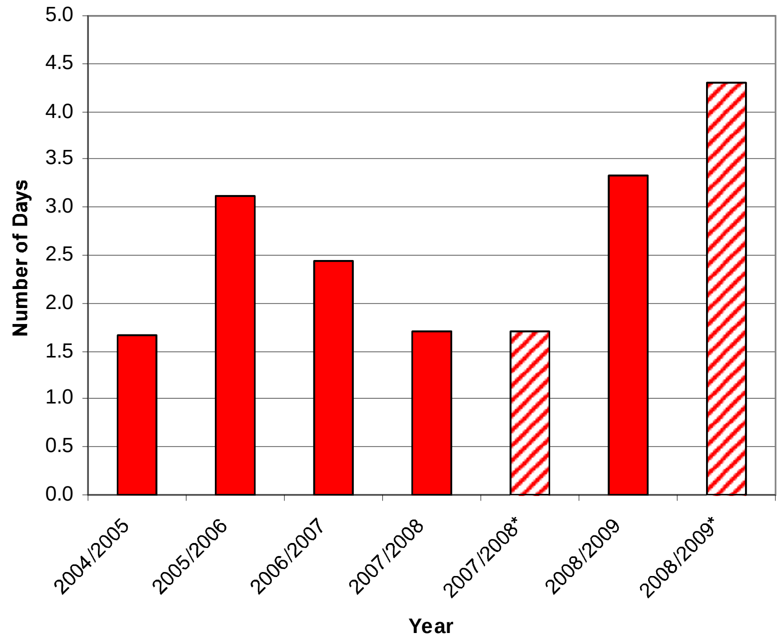

Figure 4-7. Average $PM_{2.5}$ pollution episode length for the 2004/2005 through 2008/2009 winter seasons. Solid bars indicate calculations based on observations; striped bars indicate estimates if Stage 1 and Stage 2 days were not called. NAAQS exceedances were determined using the daily BAM data collected at Del Paso Manor.

4.4 NO-BURN THRESHOLDS

The findings applicable to Question 4 are detailed in this subsection: **What should the no-burn threshold be to reduce $PM_{2.5}$ below NAAQS?**

Based on our calculations, to reduce the number of days exceeding NAAQS, the no-burn thresholds should be set as follows:

- A single stage program threshold should be about 31 μg/m^3. To derive this threshold, the median forecast bias was subtracted from the NAAQS threshold. Because the forecast bias was 4.4 μg/m^3 the threshold for a no-burn call is 35 μg/m^3 minus 4.4 μg/m^3, or 30.6 μg/m^3.
- A two-stage program threshold should be 31 μg/m^3 for Stage 1 and 35 μg/m^3 for Stage 2. To derive the Stage 2 threshold, we determined the $PM_{2.5}$ concentration for which a Stage 1 call will not be sufficient to prevent a violation of the NAAQS. To calculate this threshold, the anticipated $PM_{2.5}$ reduction resulting from a Stage 1 call was added to NAAQS and forecast error was then subtracted. Because the average reduction achieved on a Stage 1 day is 4 μg/m^3, the no-burn threshold for a Stage 2 day (ignoring forecast error) is 39 μg/m^3 (35 μg/m^3 + 4 μg/m^3). Subtracting the forecast error of 4.4 μg/m^3 results in a Stage 2 threshold of 34.6 μg/m^3 (39 μg/m^3 minus 4.4 μg/m^3).

During the 2008/2009 wood-burning season, these new thresholds would have reduced the number of days exceeding the NAAQS from 21 days to 16 days. This conclusion was determined by counting the number of days in 2008/2009 when the following criteria were met: (1) a burn ban was not called, (2) observed concentrations exceeded the NAAQS, and (3) the benefit of the Stage 1 or Stage 2 call would have lowered concentrations below the NAAQS.

The forecast error of 4.4 μg/m^3 cited above was determined by calculating the median forecast bias from days during the 2008/2009 winter season when burning was discouraged (see **Table 4-6**). The reason for using the forecast bias from the burning-discouraged category was discussed in Section 3.4.

Table 4-6. Forecast bias (forecast minus observation) for various criteria. The red cell indicates the forecast error used for the threshold calculations.

Day Type	Median Bias (μg/m^3)	Median bias for under forecasted days (μg/m^3)	Median bias for over forecasted days (μg/m^3)
All	1.8	-4.1	4.7
Burn Clearly	1.2	-3.5	3.7
Burning Discouraged	4.1	-4.4	6.4
Burn Clearly and Burning Discouraged	1.4	-3..9	4.2
Stage 1 and Stage 2	5.2	-5.3	12.7
Stage 2	5.1	-4.7	12.9
Stage 1	5.2	-7.1	11.3

4.5 BUILD-UP DAY RULE

The findings applicable to Question 5 are detailed in this subsection: **Should no-burn days be called on the day prior to high $PM_{2.5}$ concentration days to help lower pollution during $PM_{2.5}$ episodes?**

Modeling analysis shows that the average contribution of carryover from the preceding build-up day to the average 24-hr $PM_{2.5}$ concentration on the Stage day was 0.7 μg/m^3, or 2.2% of the total observed $PM_{2.5}$ concentration. The range of contributions of carryover was 0.0 to 2.7 μg/m^3, or 0 to 10.6%. Therefore, a no-burn call on the build-up day preceding high $PM_{2.5}$ concentration days will not significantly lower pollution during $PM_{2.5}$ episodes. The supporting details associated with this finding follows.

For each of the nine selected cases, the benefit of calling an additional burn ban on build-up days was determined by computing the relative difference in model-predicted Stage-day 24-hr average $PM_{2.5}$ concentrations between the two emission scenarios. Two measures of modeled carryover impact were computed: (1) a relative percentage impact, and (2) an estimated concentration impact determined by multiplying the relative percentage impact by the peak 24-hr average $PM_{2.5}$ concentration observed in Sacramento County on the Stage day.

Modeled $PM_{2.5}$ values were extracted at several receptors in Sacramento County. At 36-km resolution, most of Sacramento County is covered by four model grid cells (Figure 3-4). These grid cells divide Sacramento County into approximate quadrants. The northeast quadrant (northeast Sacramento County) covers a significant portion of the county's residential population and includes the Del Paso Manor, Folsom, and Sloughhouse $PM_{2.5}$ monitoring sites. This quadrant also contains the largest residential wood-burning emissions and is, therefore, considered representative of residential areas of Sacramento County.

Modeled carryover impacts for northeast Sacramento County are listed in **Table 4-7**. The relative carryover impact (i.e., the additional benefit of a build-up day burn curtailment) varied from case to case, but ranged between 0.1% and 3.6% in eight of the nine cases. The impact was 10.6% on January 5, 2009. The estimated concentration impact was less than 1.0 μg/m^3 on seven of the nine cases. The estimated impact was 1.5 μg/m^3 on December 10, 2008, and 2.7 μg/m^3 on January 5, 2009.

Table 4-7. Carryover impacts estimated by the BlueSky Gateway for northeast Sacramento County.

Stage Date	Relative Carryover Impact	Observed Peak 24-hour Average $PM_{2.5}$ Concentration (μg/m^3)	Estimated Carryover Impact (μg/m^3)
11/17/2008	0.44%	23.8	0.11
11/23/2008	0.90%	60.7	0.55
11/30/2008	0.18%	42.3	0.08
12/3/2008	1.04%	29.3	0.30
12/10/2008	3.62%	40.5	1.46
1/5/2009	10.62%	25.7	2.73
1/7/2009	2.26%	29.2	0.66
1/10/2009	0.07%	43.5	0.03
1/29/2009	0.28%	28.9	0.08

Carryover impacts were determined for all four Sacramento County grid cells (**Table 4-8**). The 10.62% impact in northeast Sacramento County on January 5, 2009, was the regional peak impact for all cases. Peak daily regional carryover impacts ranged from 0.39% to 3.62%, except on January 5, 2009. The daily carryover impact was greatest in northeast Sacramento County on only four of the nine cases, indicating that modeled impacts of burn curtailment often occur outside the region of peak residential burning emissions.

Table 4-8. Relative carryover impacts predicted by BlueSky Gateway for Sacramento County. Peak daily carryover impacts are boldfaced; peak carryover impact for all nine cases is italicized.

Stage Date	Northeast Sacramento County	Northwest Sacramento County	Southwest Sacramento County	Southeast Sacramento County
11/17/2008	0.44%	0.86%	**1.55%**	0.33%
11/23/2008	**0.90%**	0.86%	0.42%	0.50%
11/30/2008	0.18%	0.24%	**0.39%**	0.37%
12/3/2008	**1.04%**	-0.12%	-0.26%	1.00%
12/10/2008	**3.62%**	0.86%	0.30%	1.14%
1/5/2009	***10.62%***	1.52%	2.10%	6.86%
1/7/2009	2.26%	-0.04%	0.01%	**3.38%**
1/10/2009	0.07%	0.31%	**1.14%**	0.08%
1/29/2009	0.28%	0.20%	0.65%	**0.91%**

Time series plots show the temporal behavior of modeled $PM_{2.5}$ concentrations from both emission scenarios and illustrate how the impact of carryover evolved throughout the simulation. The time series in **Figure 4-8** indicates a day with little predicted Stage-day carryover benefit (0.18 %)**.** Significant differences between the two emission scenarios are apparent during the morning and evening hours of the build-up day as residential wood burning peaks. However, BlueSky Gateway predicted a reduction in $PM_{2.5}$ concentrations in both simulations after the evening $PM_{2.5}$ peak. This reduction may be a result of winds transporting cleaner air into the grid cell. Benefits of wood-burning curtailment achieved during the build-up day were lost as the time series from the two emission scenarios quickly converge. As a result, $PM_{2.5}$ concentrations during most of the Stage day are almost identical, and the Stage-day carryover benefit is small.

Figure 4-9 shows the observed average hourly $PM_{2.5}$ concentrations using BAM data from Folsom and Del Paso Manor for November 29 through November 30, 2008. As noted in the figure, although the modeled and observed concentrations exhibit a similar diurnal pattern, the observed concentrations are two to three times greater than the modeled concentrations. Causes of the differences between the modeled and observed concentrations are discussed in Section 4.5 under “Modeling Caveats”.

A somewhat larger (3.62%) Stage-day carryover benefit was predicted on December 10, 2008 (**Figure 4-10**). This simulation differs from the November 30, 2008 case in that the predicted benefit from burn curtailment during the build-up day is larger, and an evening clean-out was not predicted; instead, concentrations rose after the evening $PM_{2.5}$ concentration peak. As a result, the large carryover benefit generated during the build-up day carried several hours into the Stage day. However, by morning on the Stage day, predicted concentrations from both simulations were nearly the same again, though a small residual benefit remained throughout the Stage day. As a result, though the carryover impact on December 10, 2008, is larger than on November 30, 2008; the overall impact on the Stage-day 24-hr average $PM_{2.5}$ concentration is 3.6%. **Figure 4-11** shows the observed average hourly $PM_{2.5}$ concentrations using data from Folsom and Del Paso Manor for December 9, 2008, through December 10, 2008. As noted in the figure, there is a marked difference in the modeled and observed concentrations on December 10, 2008. Causes of the differences between the modeled and observed concentrations are discussed in Section 4.5 under "Modeling Caveats".

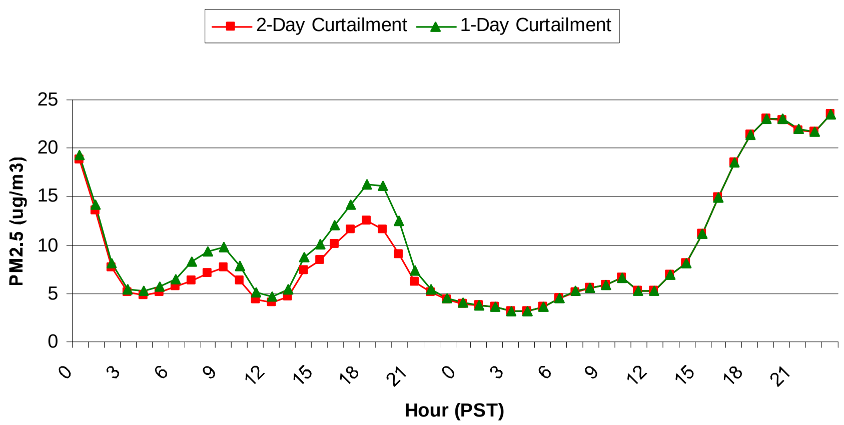

Figure 4-8. Time series of BlueSky Gateway $PM_{2.5}$ concentrations in northeast Sacramento County for November 29 through November 30, 2008, for one-day and two-day residential wood-burning curtailment scenarios.

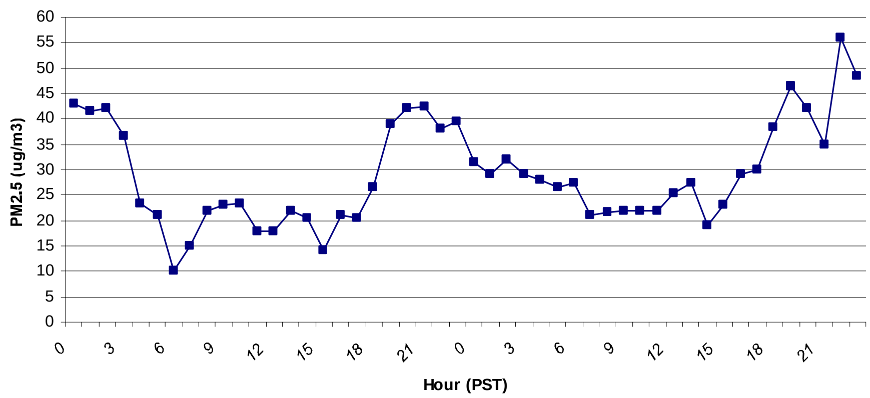

Figure 4-9. Time series of observed average hourly $PM_{2.5}$ concentrations using data from Folsom and Del Paso Manor for November 29 through November 30, 2008.

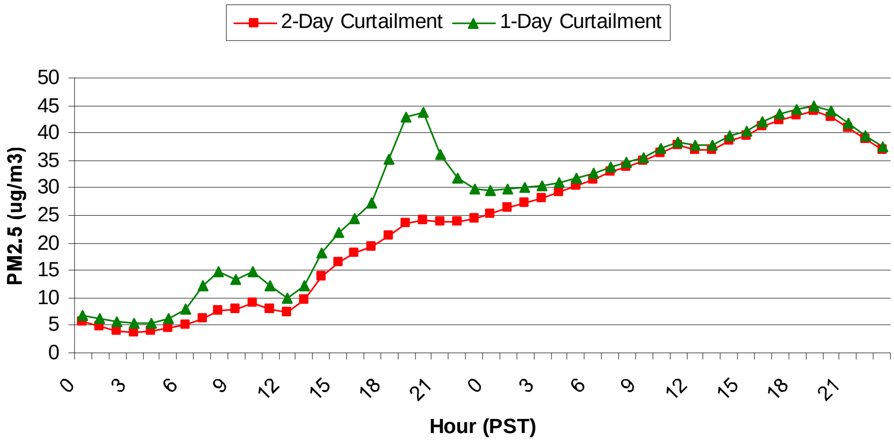

Figure 4-10. Time series of BlueSky Gateway $PM_{2.5}$ concentrations in northeast Sacramento County for December 9, 2008, through December 10, 2008, for one-day and two-day residential wood-burning curtailment scenarios.

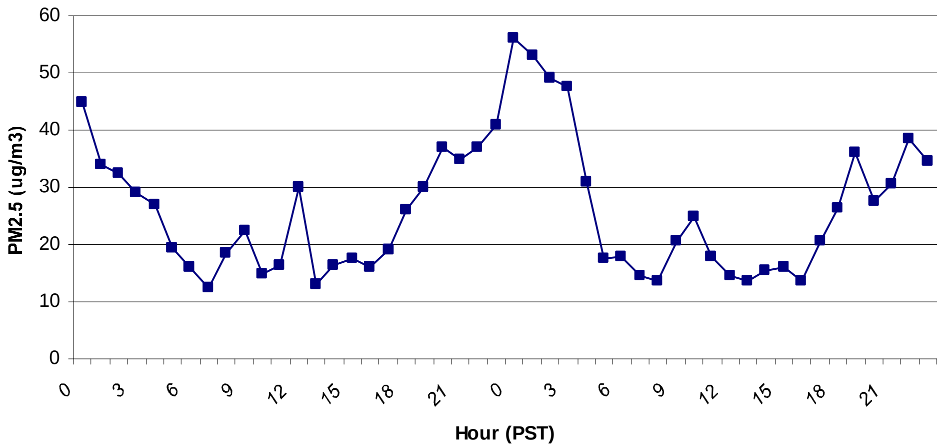

Figure 4-11. Time series of observed average hourly $PM_{2.5}$ concentrations using data from Folsom and Del Paso Manor for December 9, 2008, through December 10, 2008.

Modeling Caveats

The following limitations should be considered when interpreting results from the BlueSky Gateway modeling system:

- Because of the relatively coarse (36 km) horizontal grid resolution, predicted $PM_{2.5}$ concentrations in Sacramento County are only modeled with 4 grid cells. Emissions from localized sources are diluted into relatively large model grid volumes. This artificially smoothes over localized emission patterns, and tends to result in an under prediction of $PM_{2.5}$ concentrations.
- Wind fields modeled at 36 km resolution are not always representative of the observed localized wind fields that drive dispersion characteristics at local scales. As a result,

differences between modeled and observed $PM_{2.5}$ concentrations are to be expected, as $PM_{2.5}$ concentrations can be highly sensitivity to the local wind field.

- Predicted $PM_{2.5}$ concentrations are subject to any biases and errors inherent in the meteorological model used to produce meteorological data for the air quality model.
- Sensitivity simulations were performed with 100% curtailment in residential wood burning, whereas actual curtailment is likely less than 100%.

5. REFERENCES

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APPENDIX A

ADDITIONAL FINDINGS ON THE EFFECTIVENESS OF THE BURNING CURTAILMENT PROGRAM TOWARD MEETING THE NAAQS

A. INTRODUCTION

After completing the report entitled “Evaluation of Sacramento Metropolitan Air Quality Management District’s ‘Check Before You Burn’ Program” on May 6, 2009, STI conducted additional modeling analyses to provide additional information to address the question: “What is the effectiveness of the burning curtailment program toward meeting the NAAQS?” This appendix reports on the findings from the modeling analyses. The addition of this appendix is the reason for the report update on August 24, 2009.

For these analyses, STI used a three-dimensional photochemical model to estimate $PM_{2.5}$ concentrations under three scenarios for 37 winter days in 2008/2009. The model used estimated emissions from residential wood burning (1) with no burning restrictions; (2) under a Stage 1 burn ban; and (3) under a Stage 2 burn ban. The differences in $PM_{2.5}$ concentrations between the no-burning restriction scenario and each burn ban scenario were then calculated to provide an estimate of the $PM_{2.5}$ reduction attributable to the Stage 1 and Stage 2 burn bans. Note that the three-dimensional photochemical model includes both secondary and primary $PM_{2.5}$; therefore, the benefits reported in the appendix are reductions in total $PM_{2.5}$ concentrations due to wood-burning restrictions.

A.1 SUMMARY OF FINDINGS

In summary, modeling analyses show that

- the average benefit of a Stage 1 burn ban on the 24-hr average $PM_{2.5}$ concentration was 5.2 $\mu g/m^3$, or 13.7% of the total $PM_{2.5}$ concentration;
- the average benefit of a Stage 2 burn ban was 6.4 $\mu g/m^3$, or 16.9% of the total $PM_{2.5}$ concentration;
- the maximum benefit of a Stage 1 burn ban was 8.7 $\mu g/m^3$, or 18.4%; and
- the maximum benefit of a Stage 2 burn ban was 10.8 $\mu g/m^3$, or 22.7%.

These modeling results are consistent with the results from the data analysis described in the main report.

A.2 METHOD

STI used the BlueSky Gateway air quality modeling system. BlueSky Gateway is an operational $PM_{2.5}$ forecasting system developed for the U.S. Forest Service to predict $PM_{2.5}$ concentrations resulting from wildfires and other emissions sources on a national scale at coarse (36 km) resolution. BlueSky Gateway combines meteorological predictions from the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) (Grell et al., 1994; Dudhia, 1993) with air quality predictions from the Community Multiscale Air Quality (CMAQ) model (ENVIRON International Corporation, 2008). STI has operated BlueSky Gateway twice daily since its inception in the summer of 2007 (Craig et al., 2007) .

Though BlueSky Gateway was designed primarily to track and predict $PM_{2.5}$ concentrations from wildfires, the modeling system is run with full gaseous and aerosol chemistry to predict the fate of $PM_{2.5}$ emissions from all types of natural and anthropogenic sources, including residential wood burning. Details on the use of BlueSky Gateway to address the questions posed by SMAQMD are presented below. Additional details can be found in *Development and Operation of National CMAQ-Based $PM_{2.5}$ Forecast System for Fire Management* (Craig et al., 2007).

STI performed numerous BlueSky Gateway simulations to evaluate the benefit of Stage 1 and Stage 2 burn bans on polluted days. Thirty-seven cases from the 2008/2009 winter burning season, as shown in **Table A-1**, were selected for this analysis. In most cases, $PM_{2.5}$ concentrations were predicted to be high enough to issue a Stage 1 or Stage 2 burn ban. To provide initialized concentration fields for the simulations, BlueSky Gateway models with no burning restrictions were run for several days prior to each case date until midnight PST of the case date.

For each case date, three simulations were performed:

1. Base case simulation with no burning curtailment in Sacramento County.
2. Sensitivity simulation with Stage 1 burn restrictions applied to Sacramento County.
3. Sensitivity simulation with Stage 2 burn restrictions applied to Sacramento County.

Wood combustion emission rates for the Stage 1 and Stage 2 burn-ban scenarios were developed by applying 57% and 70% across-the-board reduction factors to the Sacramento County 2009 wood smoke emissions estimates. Reduction factors were provided by the District on the basis of burn ban compliance rates determined by survey.

Simulations were executed for a 24-hour period starting at midnight PST on the case date, for consistency with the timing of actual burn curtailment (midnight to midnight on the day for which a burn ban is issued). The modeled difference in $PM_{2.5}$ concentrations between the base case simulation and the sensitivity simulations yields the relative benefit (expressed as a percent reduction in concentration) of a Stage 1 or Stage 2 burn ban. A concentration benefit can be estimated by multiplying the relative percentage benefit by the observed peak 24-hr average $PM_{2.5}$ concentration in Sacramento County.

Table A-1. Cases selected for BlueSky Gateway modeling analysis.

Case Date	Observed Peak 24-hour Average $PM_{2.5}$ Concentration ($\mu g/m^3$)	Burn Category
11/17/2008	23.8	Stage 1
11/22/2008	49.4	Discouraged
11/23/2008	60.7	Stage 2
11/24/2008	43.0	Stage 2
11/25/2008	36.3	Stage 1
11/26/2008	43.1	Stage 1
11/27/2008	30.5	Stage 2
11/28/2008	30.0	Stage 2
11/30/2008	42.3	Stage 1
12/3/2008	29.3	Stage 2
12/4/2008	30.3	Stage 2
12/5/2008	45.5	Stage 1
12/6/2008	38.9	Stage 2
12/7/2008	32.0	Stage 1
12/10/2008	40.5	Stage 2
12/11/2008	49.3	Stage 2
12/12/2008	69.8	Discouraged
1/5/2009	25.7	Stage 2
1/7/2009	29.2	Stage 2
1/10/2009	43.5	Stage 2
1/11/2009	55.2	Stage 2
1/12/2009	38.0	Stage 2
1/13/2009	43.5	Stage 2
1/14/2009	50.2	Stage 2
1/15/2009	42.5	Stage 2
1/16/2009	50.1	Stage 2
1/17/2009	45.6	Stage 2
1/18/2009	28.1	Stage 2
1/19/2009	28.3	Stage 2
1/20/2009	23.2	Stage 2
1/29/2009	28.9	Stage 1
1/30/2009	39.7	Stage 2
1/31/2009	35.1	Stage 2
2/1/2009	26.7	Stage 2
2/2/2009	29.5	Stage 2
2/3/2009	28.0	Stage 2
2/4/2009	24.7	Stage 1

Estimates of residential wood combustion emissions for Sacramento County were developed from 2009 county-level average winter day emissions estimates provided by the District. These emissions were based on the California Air Resources Board (ARB) version 1.06 emissions inventory, which uses a 2002 base year. County-level emissions were spatially allocated according to census data on households with wood heating as the primary heating source. Emissions were allocated to model grid cells with the Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System (Houyoux et al., 2000).

Residential wood combustion emissions outside of Sacramento County were taken from the 2002 National Emission Inventory (NEI), processed through SMOKE, and projected to 2007 by using growth factors generated by EPA's Economic Growth Analysis System (EGAS) version 4.0 (E.H. Pechan & Associates, 2001). For wood combustion emissions from all counties, the standard SMOKE speciation profile was used to disaggregate total $PM_{2.5}$ emissions into individual model species (**Table A-2**), and the default SMOKE diurnal profile for residential wood combustion was replaced with a more appropriate profile developed by the ARB.

Table A-2. SMOKE $PM_{2.5}$ speciation profile

Profile #	Model Species	Model Species Name	Mass Fraction
22061	PEC	Primary elemental carbon	0.1077
22061	PMFINE	Fine mode PM (metals and other species)	0.3208
22061	PNO_3	Primary nitrate aerosol	0.0022
22061	POA	Primary organic aerosol	0.5656
22061	PSO_4	Primary sulfate aerosol	0.0037

Because of the relatively coarse horizontal resolution of BlueSky Gateway (36 km), peak concentrations may be underestimated by the model as localized emissions are artificially diluted into relatively large model grid cells. **Figure A-1** illustrates the size of BlueSky Gateway model grid cells relative to Sacramento County. To address the effects of such coarse resolution, STI avoided using absolute modeled concentration differences and instead used the *relative* difference between the base case (no burn restriction) scenario and the Stage 1 and Stage 2 sensitivity scenarios to assess the benefit of the burn ban.

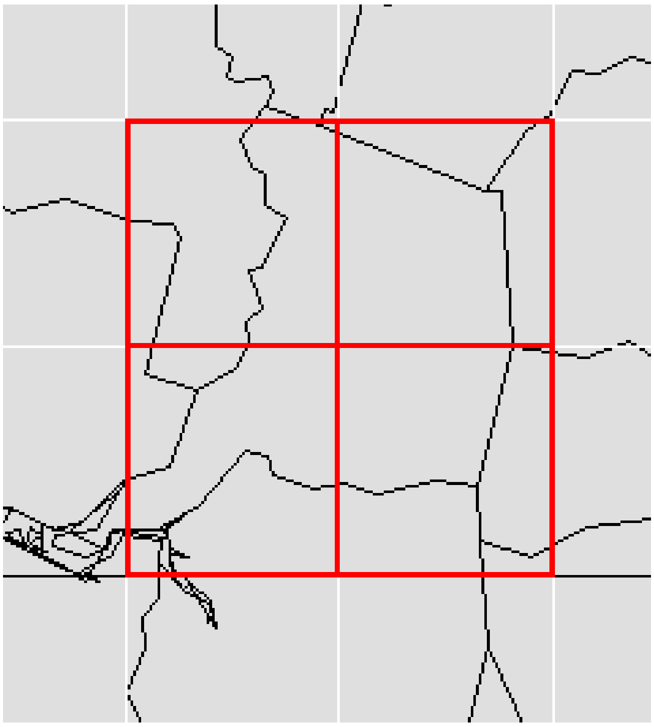

Figure A-1. BlueSky Gateway model grid in the Sacramento County region. Grid cells highlighted in red indicate the four cells that encompass most of Sacramento County.

A.3 MODELING CAVEATS

The following limitations should be considered when interpreting results from the modeling analyses:

- Because of the relatively coarse horizontal grid resolution used in the model, $PM_{2.5}$ concentrations are only estimated in four grid cells, which cover Sacramento County. Emissions from localized sources are diluted in the relatively large model grid volumes. This dilution artificially smoothes over localized emission patterns and tends to result in an under-estimation of $PM_{2.5}$ concentrations.
- Wind fields modeled at 36-km resolution are not always representative of the localized winds that drive transport and dispersion on local scales. As a result, differences between modeled and observed $PM_{2.5}$ concentrations are to be expected, as $PM_{2.5}$ concentrations can be highly sensitive to the local winds.
- Estimations of $PM_{2.5}$ concentrations are subject to any biases and errors inherent in the meteorological model used to provide data to the air quality model.

A.4 FINDINGS

Modeling analysis results show that the average benefit of a Stage 1 burn ban on the regional peak 24-hr average $PM_{2.5}$ concentration was 5.2 µg/m^3, or 13.7% of the total observed $PM_{2.5}$ concentration. The average benefit of a Stage 2 burn ban was 6.4 µg/m^3, or 16.9% of the total observed $PM_{2.5}$ concentration. The range of benefits of a Stage 1 burn ban was from 2.2 to 8.7 µg/m^3, or from 7.8 to 18.4%. The range of benefits of a Stage 2 burn ban was from 2.7 to 10.8 µg/m^3, or from 9.7 to 22.7%.

Modeled estimates of $PM_{2.5}$ concentrations were extracted at several receptors in Sacramento County. At 36-km resolution, most of Sacramento County is covered by four model grid cells (Figure A-1). These grid cells divide Sacramento County approximately into quadrants. The northeast quadrant (northeast Sacramento County) covers a significant portion of the county's residential population and includes the Del Paso Manor, Folsom, and Sloughhouse $PM_{2.5}$ monitoring sites. This quadrant is responsible for the largest amount of residential wood-burning emissions and is, therefore, considered representative of residential areas of Sacramento County.

Modeled Stage 1 and Stage 2 burn-ban benefits for northeast Sacramento County are listed in **Table A-3**. Modeled benefits varied from case to case, but were never less than 2.2 µg/m^3 for a Stage 1 burn ban, or 2.7 µg/m^3 for a Stage 2 burn ban. Relative benefits of Stage 1 burn bans exceeded 10% for 31 of 37 modeled cases, while relative benefits of Stage 2 burn bans exceeded 10% for all but one modeled case. The maximum modeled relative benefit occurred on November 17, 2008, with relative benefits of 18.4% and 22.7% for Stage 1 and Stage 2 burn bans, respectively. The maximum modeled concentration benefit occurred on January 16, 2009, with benefits of 8.7 µg/m^3 and 10.8 µg/m^3 for Stage 1 and Stage 2 burn bans, respectively.

Relative burn-ban benefits were determined for all four Sacramento County grid cells (**Table A-4**). The maximum relative benefit from Stage 1 and Stage 2 burn bans was in northeast Sacramento County, on November 17, 2009. In all cases, benefits were greater in northeast Sacramento County than in other parts of Sacramento County, as residential wood-burning emissions were highest in northeast Sacramento County. Southwest Sacramento County had the smallest benefit for all but one case.

Table A-3. Modeled benefits of Stage 1 and Stage 2 burn bans estimated by the BlueSky Gateway for northeast Sacramento County.

Stage Date	Observed Peak 24-hour Average $PM_{2.5}$ Concentration ($\mu g/m^3$)	Relative Stage 1 Benefit	Estimated Stage 1 Benefit ($\mu g/m^3$)	Relative Stage 2 Benefit	Estimated Stage 2 Benefit ($\mu g/m^3$)
11/17/2008	23.8	18.4%	4.4	22.7%	5.4
11/22/2008	49.4	13.5%	6.7	16.7%	8.3
11/23/2008	60.7	12.6%	7.6	15.5%	9.4
11/24/2008	43.0	9.9%	4.2	12.2%	5.2
11/25/2008	36.3	11.9%	4.3	14.8%	5.4
11/26/2008	43.1	12.7%	5.5	15.7%	6.8
11/27/2008	30.5	17.4%	5.3	21.4%	6.5
11/28/2008	30.0	12.8%	3.8	15.8%	4.7
11/30/2008	42.3	16.9%	7.1	20.8%	8.8
12/3/2008	29.3	13.0%	3.8	16.0%	4.7
12/4/2008	30.3	8.9%	2.7	10.9%	3.3
12/5/2008	45.5	16.8%	7.7	20.8%	9.5
12/6/2008	38.9	12.4%	4.8	15.3%	6.0
12/7/2008	32.0	13.4%	4.3	16.5%	5.3
12/10/2008	40.5	8.2%	3.3	10.1%	4.1
12/11/2008	49.3	9.7%	4.8	12.0%	5.9
12/12/2008	69.8	7.8%	5.5	9.7%	6.8
1/5/2009	25.7	8.6%	2.2	10.6%	2.7
1/7/2009	29.2	11.8%	3.4	14.5%	4.2
1/10/2009	43.5	16.8%	7.3	20.8%	9.1
1/11/2009	55.2	12.2%	6.7	15.0%	8.3
1/12/2009	38.0	17.5%	6.7	21.6%	8.2
1/13/2009	43.5	16.6%	7.2	20.6%	9.0
1/14/2009	50.2	15.3%	7.7	19.0%	9.6
1/15/2009	42.5	16.6%	7.0	20.5%	8.7
1/16/2009	50.1	17.4%	8.7	21.5%	10.8
1/17/2009	45.6	16.7%	7.6	20.7%	9.4
1/18/2009	28.1	16.0%	4.5	19.8%	5.6
1/19/2009	28.3	15.1%	4.3	18.8%	5.3
1/20/2009	23.2	14.1%	3.3	17.4%	4.0
1/29/2009	28.9	16.6%	4.8	20.5%	5.9
1/30/2009	39.7	14.6%	5.8	18.0%	7.2
1/31/2009	35.1	11.2%	3.9	13.8%	4.8
2/1/2009	26.7	11.9%	3.2	14.8%	3.9
2/2/2009	29.5	11.9%	3.5	14.6%	4.3
2/3/2009	28.0	14.8%	4.2	18.3%	5.1
2/4/2009	24.7	14.9%	3.7	18.2%	4.5

Table A-4. Relative benefit (%) of Stage 1 and Stage 2 burn bans predicted by BlueSky Gateway for Sacramento County. The maximum and minimum relative benefits at each receptor are boldfaced.

Stage Date	Northeast Sacramento County		Northwest Sacramento County		Southwest Sacramento County		Southeast Sacramento County	
	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
11/17/2008	**18.4**	**22.7**	8.7	10.8	4.3	5.3	9.1	11.2
11/22/2008	13.5	16.7	4.9	6.0	2.3	2.9	3.6	4.5
11/23/2008	12.6	15.5	3.2	3.9	1.3	1.6	2.9	3.6
11/24/2008	9.9	12.2	3.3	4.1	0.8	1.0	**2.0**	**2.5**
11/25/2008	11.9	14.8	4.7	5.8	2.1	2.6	3.9	4.8
11/26/2008	12.7	15.7	2.2	2.6	0.9	1.1	4.0	5.0
11/27/2008	17.4	21.4	4.9	6.1	2.2	2.7	9.9	12.2
11/28/2008	12.8	15.8	2.2	2.7	1.0	1.2	4.5	5.5
11/30/2008	16.9	20.8	6.1	7.5	2.2	2.6	5.6	6.9
12/3/2008	13.0	16.0	4.4	5.4	2.1	2.6	4.9	6.1
12/4/2008	8.9	10.9	1.9	2.4	1.1	1.3	3.8	4.7
12/5/2008	16.8	20.8	5.9	7.3	4.5	5.5	9.8	12.0
12/6/2008	12.4	15.3	3.7	4.5	2.6	3.2	7.9	9.7
12/7/2008	13.4	16.5	3.6	4.4	1.9	2.4	6.9	8.5
12/10/2008	8.2	10.1	**1.7**	**2.0**	0.9	1.1	3.9	4.8
12/11/2008	9.7	12.0	2.1	2.5	1.2	1.4	5.2	6.4
12/12/2008	**7.8**	**9.7**	2.8	3.4	**0.7**	**0.9**	2.1	2.6
1/5/2009	8.6	10.6	5.1	6.2	1.3	1.6	2.3	2.8
1/7/2009	11.8	14.5	3.0	3.6	1.7	2.1	5.2	6.4
1/10/2009	16.8	20.8	6.3	7.7	5.0	6.1	10.7	13.1
1/11/2009	12.2	15.0	3.5	4.3	2.8	3.5	8.6	10.5
1/12/2009	17.5	21.6	6.8	8.4	**7.0**	**8.6**	11.7	14.5
1/13/2009	16.6	20.6	6.7	8.3	5.3	6.5	11.4	14.1
1/14/2009	15.3	19.0	5.3	6.5	3.9	4.8	9.4	11.7
1/15/2009	16.6	20.5	7.0	8.6	4.1	5.1	8.8	10.9
1/16/2009	17.4	21.5	7.1	8.7	5.0	6.1	**11.8**	**14.5**
1/17/2009	16.7	20.7	5.8	7.2	4.0	4.9	9.8	12.0
1/18/2009	16.0	19.8	6.2	7.7	4.8	5.9	9.9	12.3
1/19/2009	15.1	18.8	6.8	8.4	6.6	8.1	10.4	12.9
1/20/2009	14.1	17.4	6.4	7.9	5.6	6.9	8.5	10.5
1/29/2009	16.6	20.5	5.9	7.3	3.4	4.2	6.0	7.6
1/30/2009	14.6	18.0	4.9	6.1	3.3	4.0	9.2	11.3
1/31/2009	11.2	13.8	3.1	3.8	1.8	2.3	7.2	8.8
2/1/2009	11.9	14.8	4.0	4.9	2.8	3.5	7.8	9.6
2/2/2009	11.9	14.6	5.3	6.6	2.2	2.7	3.5	4.4
2/3/2009	14.8	18.3	7.1	8.8	2.4	2.9	4.6	5.7
2/4/2009	14.9	18.2	**8.7**	**10.9**	3.1	3.9	5.0	6.3

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