Wintertime Air Toxics from Wood Smoke in Sacramento

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Sacramento Metropolitan Air Quality Management District (SMAQMD)
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Prepared by

Hilary Hafner
Nathan Pavlovic
Mike McCarthy
Anondo Mukherjee
Steven Brown

Sonoma Technology, Inc.
1450 N. McDowell Blvd., Suite 200
Petaluma, CA 94954-6515
Ph. 707.665.9900 | F 707.665.9800
sonomatech.com

Prepared for

Janice Lam Snyder
Stephen D'Andrea
Aleta Kennard (Retired)

Sacramento Metropolitan Air Quality
Management District (SMAQMD)
777 12th Street
Sacramento, CA 95814
Ph. 916.874.4800
airquality.org

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Cover photo illustrates the Del Paso Manor site during instrument collocation. See Section 2 for more information.

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Jaspreet Gosal and Frank Wulff (SMAQMD) conducted and supported field work, Lori Kobza developed the public outreach strategy, and Marc Cooley assisted with the survey portion of the project. The phone survey was developed, conducted, and reported by Meta Research; their report is included as Appendix A. Funding was from an EPA community air toxics grant and SMAQMD. The California Air Resources Board provided access and power to their monitoring site at T Street.

Disclaimer

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Executive Summary

Overview

In Sacramento, California, residential wood smoke is an important source of wintertime particulate matter under 2.5 microns in diameter ($PM_{2.5}$), and is strongly suspected to be the main source of some hazardous air pollutants (HAPs), including acetaldehyde, acrolein, acetonitrile, and naphthalene. Disadvantaged communities may be disproportionately impacted by wood smoke and the HAPs associated with wood smoke. The Sacramento Metropolitan Air Quality Management District (SMAQMD) sought to improve its general understanding of HAPs from sources such as wood smoke, and develop its capabilities for mitigating any associated environmental justice (EJ) issues from exposure to HAPs through a grant funded by the U.S. Environmental Protection Agency (EPA).

Enhanced monitoring of HAPs and other related pollutants was conducted through an intensive two-month measurement campaign from December 2016 through January 2017 in Sacramento County. The campaign was conducted during the period that the Check Before You Burn program is in effect. A combination of traditional regulatory grade instruments, filter and canister samplers, new low-cost sensors, and community phone survey data were used to address the research questions. Sensor technology was used to gain more spatial coverage at lower costs compared to the use of traditional instruments.

The project focused on these research questions:

1. What are the concentrations of HAPs in various communities in Sacramento?
2. To what degree does wood smoke contribute to HAPs in these communities?
3. Are disadvantaged communities disproportionately impacted by wood smoke HAPs?
4. Are there changes that can be made to SMAQMD's air quality outreach program to reduce HAPs?

Study Design

This was the first study to examine the contribution of wood burning to air toxics in Sacramento. Data were collected using a variety of measurement techniques, performance of the instrumentation was characterized, and local-scale pollutant gradients driven by local-scale wood smoke emissions were assessed. Measurements collected included gaseous HAPs, black carbon (BC), speciated particulate matter (PM), and PM mass. Wood smoke PM in Sacramento was quantified using Aethalometer measurements of BC and filter measurements of levoglucosan. Multi-channel Aethalometer measurements were used to apportion BC into wood burning and fossil fuel contributions.

Monitoring was conducted at three tiers of locations:

- **Tier 1 sites** – two existing regulatory monitoring stations, at Del Paso Manor and T Street, supplemented with additional instrumentation, sampling, and low-cost sensors, which are likely representative of types of non-EJ areas where there currently is no monitoring;
- **Tier 2 sites** – four new monitoring sites with regulatory-grade monitoring equipment, plus low-cost sensors; and
- **Tier 3 sites** – nine new sites with low-cost sensors.

Each of the non-EJ Tier 1 sites was paired with a Tier 2 site in a nearby EJ community. There were two additional Tier 2 sites, one in a non-EJ and one in an EJ community. Each of the Tier 1 and 2 sites were associated with up to three of the Tier 3 sites. A map of the study area is shown in **Figure ES-1**. In conjunction with air monitoring, a phone survey was conducted by Meta Research to understand wood burning behavior in the communities where air monitoring was conducted. Specifically, the objectives of the survey were to assess wood burning activity, evaluate wood burning activity by type of device used to burn, and compare wood burning activity between EJ and non-EJ communities. Air pollution data were then combined with phone survey results on wood burning practices. Together, pollution gradients and survey information were assessed to understand relative air toxics concentrations between EJ and non-EJ communities. Findings from the phone survey and measurements were also used to inform the SMAQMD's Check Before You Burn program.

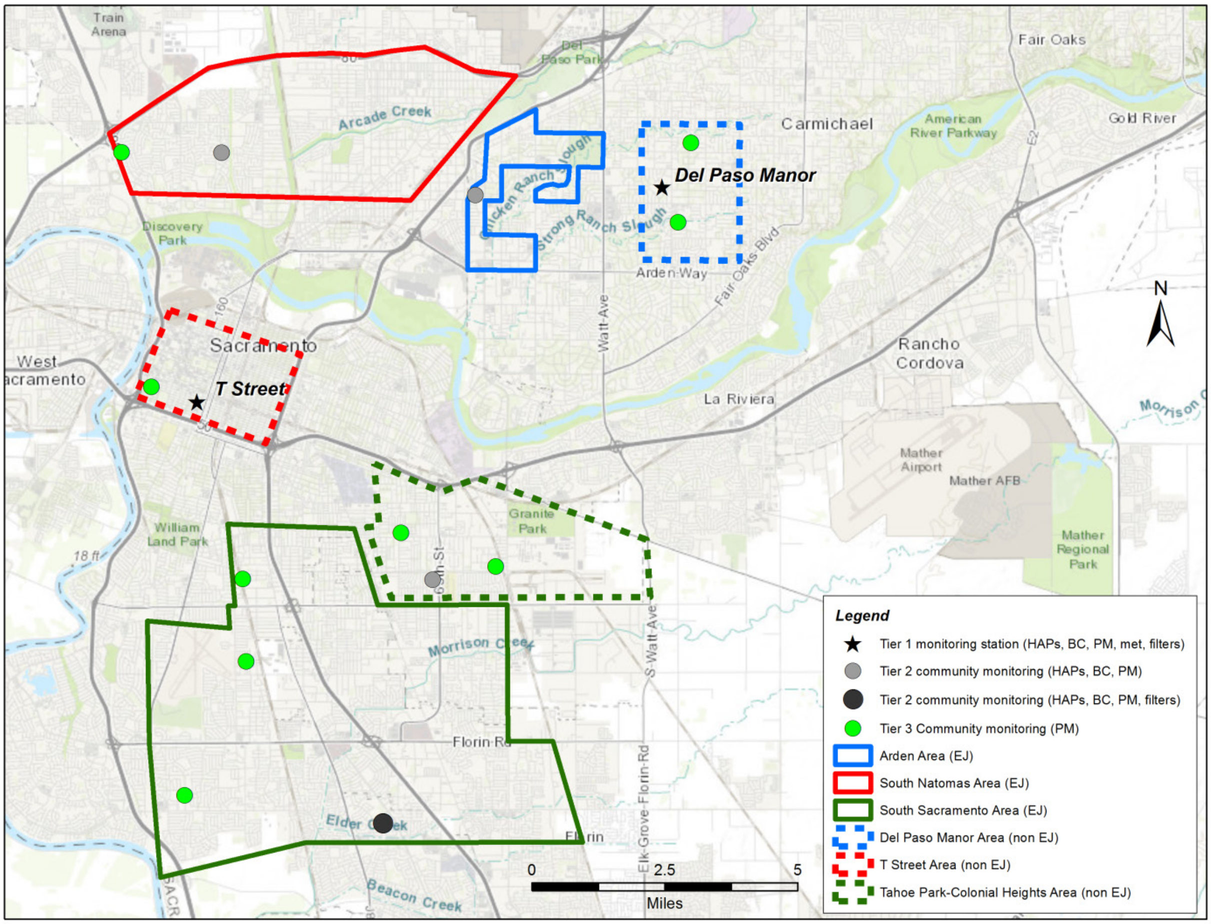


Figure ES-1. The monitored Sacramento communities, site locations and measurements. Legend: HAPs are hazardous air pollutants, BC is black carbon, PM is particulate matter, met is meteorology, and filters are for levoglucosan. Solid lines outline EJ areas, and dashed lines outline non-EJ areas. Tiers are explained in the preceding text.

Key Findings

This study quantified concentrations of HAPs in various communities in Sacramento; determined to what degree wood smoke contributes to HAPs in these communities; and improved the understanding of whether EJ communities are disproportionately impacted by wood smoke HAPs. Conclusions include:

Wood burning was not found to contribute to HAPs. The data were investigated in a number of ways to assess wood smoke contributions to HAPs in Sacramento communities. The analyses consistently showed no wood burning "signal" of the HAPs studied. All analyses (temporal, ratio:ratio, source apportionment, etc.) gave this result, which provides added confidence in this assessment; see Sections 3.1 through 3.5.

Fossil fuel–related HAPs and BC concentrations were highest in EJ communities. Concentrations of six HAPs (benzene, toluene, ethylbenzene, m,p-xylene, iso-octane, and acrolein) and BC from fossil fuel (BC_{ff}) were significantly higher at EJ sites compared to non-EJ sites. See Sections 3.1 and 3.3 for details.

BC from wood burning (BC_{wb}) was highest in non-EJ communities. BC_{wb} concentrations were significantly higher at non-EJ sites than EJ sites, while total PM was not significantly different between EJ and non-EJ sites. Of the monitoring sites in the study, both BC and BC_{wb} concentrations were highest at the Del Paso Manor site. Further, at the two Tier 1 monitoring sites (Del Paso Manor and T Street), wood burning contributed 29% to 39% of the $PM_{2.5}$ on nights when filters were collected. See Sections 3.2, 3.3, and 3.5 for details.

Phone survey results were consistent with study measurements. The only significant differences in the survey results between EJ and non-EJ areas were that non-EJ residents burn with indoor devices more often than EJ residents do. Indoor devices include fireplaces, wood burning stoves and inserts, and pellet stoves. See Section 4 and Appendix A for details.

Low-cost sensors were very reliable and useful to assess spatial differences in PM. The AirBeams demonstrated very high sensor-to-sensor precision during the pre-and post-study collocation periods. This signifies that the AirBeam sensors provided stable and consistent measurements over a range of different wintertime meteorological conditions, including the varying chemical composition and size distribution of PM. It also means that the differences in concentration measurements between AirBeams were real and quantifiable. See Sections 3.4 and 3.5 for details.

Low-cost sensors are modestly accurate. The correlation of the 1-hr PM values from the AirBeams and the Met One Beta Attenuation Monitor (BAM) 1020s (a traditional regulatory grade instrument) was modest [Pearson coefficient of determination (R^2) = 0.60], demonstrating moderate sensor accuracy that is typical for well-performing sensors. See Section 3.4.3 for details.

In summary, although wood burning was not a significant source of HAPs, it was a significant source of $PM_{2.5}$. While not a goal of the study, low-cost sensor technology was successfully used to gain more spatial coverage of PM concentrations at a lower cost compared to the use of traditional instruments.

1. Introduction

1.1 Project Objectives

The Sacramento Metropolitan Air Quality Management District (SMAQMD) sought to improve its general understanding of key hazardous air pollutants (HAPs) from wood smoke and mobile sources, and develop its capabilities for mitigating any associated environmental justice (EJ) issues from exposure to HAPs through a grant funded by the U.S. Environmental Protection Agency (EPA). According to the Sacramento area emissions inventory, residential wood smoke constitutes more than 50 percent of wintertime emissions of particulate matter under 2.5 microns in diameter ($PM_{2.5}$), and may therefore be the main source of some HAPs, including acetaldehyde, acrolein, acetonitrile, and naphthalene.

The project focused on these research questions:

1. What are the concentrations of HAPs in various communities in Sacramento?
2. To what degree does wood smoke contribute to HAPs in these communities?
3. Are disadvantaged communities disproportionately impacted by wood smoke HAPs?
4. Are there changes that can be made to SMAQMD's air quality outreach program to reduce HAPs?

Enhanced monitoring of HAPs and other related pollutants was conducted during an intensive measurement campaign from December 2016 through January 2017. A combination of traditional regulatory grade instruments, new low-cost sensors, and community survey data were used to address the research questions. Sensor technology was used to gain more spatial coverage at lower costs compared to the use of traditional instruments.

1.2 Background

According to the Sacramento area emissions inventory, wood smoke from residential burning causes more than 50 percent of emissions for wintertime $PM_{2.5}$ in Sacramento, and other ambient pollution studies have indicated that wood smoke is a major source of PM (Hasheminassab et al., 2014; Kleeman et al., 2009). Wood smoke toxics include formaldehyde, acetaldehyde, and acetonitrile (Holzinger et al., 1999), as well as acrolein, polycyclic organic matter (POM), benzene, and dioxins (McDonald et al., 2000; Schauer et al., 2001), most of which are listed among EPA's 30 Urban Air Toxics of Concern and are leading drivers of risk nationally (McCarthy et al., 2007). Despite the known health effects of HAPs and the fact that wood burning can be a source of HAPs, the SMAQMD has little monitoring data on ambient HAPs levels, wood smoke contributions to HAPs, and whether EJ communities are more affected by wood smoke than non-EJ communities.

Wood smoke contains solid, liquid, and gas components, many of which are known to cause adverse health effects. Wood smoke PM is not recognized as a separate carcinogenic mixture by the Office of

Environmental Health Hazard Assessment (OEHHA) or the EPA, but carcinogenic compounds such as acetonitrile, 1,3-butadiene, benzene, polycyclic aromatic hydrocarbons (PAHs), and formaldehyde are all components of wood smoke emissions (Naeher et al., 2007). In this project, selected gaseous air toxics were targeted to attempt to quantify whether they correlated with wood smoke PM concentrations during wintertime wood burning episodes.

1.3 Study Design Overview

Measurements included gaseous HAPs, black carbon (BC), speciated PM, and PM mass. Wood smoke PM in Sacramento was quantified using Aethalometer measurements of BC and filter measurements of levoglucosan. Multi-channel Aethalometer measurements have been widely used to quantify wood smoke contributions to black carbon (Sandradewi et al., 2008b; Allen et al., 2004; Zhang et al., 2017). Levoglucosan is a known tracer of wood smoke (Sullivan et al., 2008; Fraser and Lakshmanan, 2000; Fine et al., 2004; Simoneit et al., 1999). HAP and filter measurements were collected on a forecast basis, on days and nights forecasted to have high $PM_{2.5}$. In conjunction with air monitoring, a phone survey was conducted by Meta Research to understand wood burning behavior in the communities where air monitoring was conducted. The specific objectives of the survey were to assess wood burning activity, evaluate wood burning activity by type of device used to burn, and compare wood burning activity between EJ and non-EJ communities.

Monitoring was conducted at three types of locations:

1. **Tier 1 sites** – two existing regulatory monitoring stations, supplemented with additional instrumentation, sampling and low-cost sensors.
2. **Tier 2 sites** – four new monitoring sites, with regulatory grade monitoring equipment plus low-cost sensors.
3. **Tier 3 sites** – nine new sites with low-cost sensors.

Each of the Tier 1 sites was paired with a Tier 2 site in a nearby EJ community. There were two additional Tier 2 sites, one in a non-EJ and one in an EJ community. Each of the Tier 1 and 2 sites were associated with one to three Tier 3 sites. A map of the study area is shown in **Figure 1**.

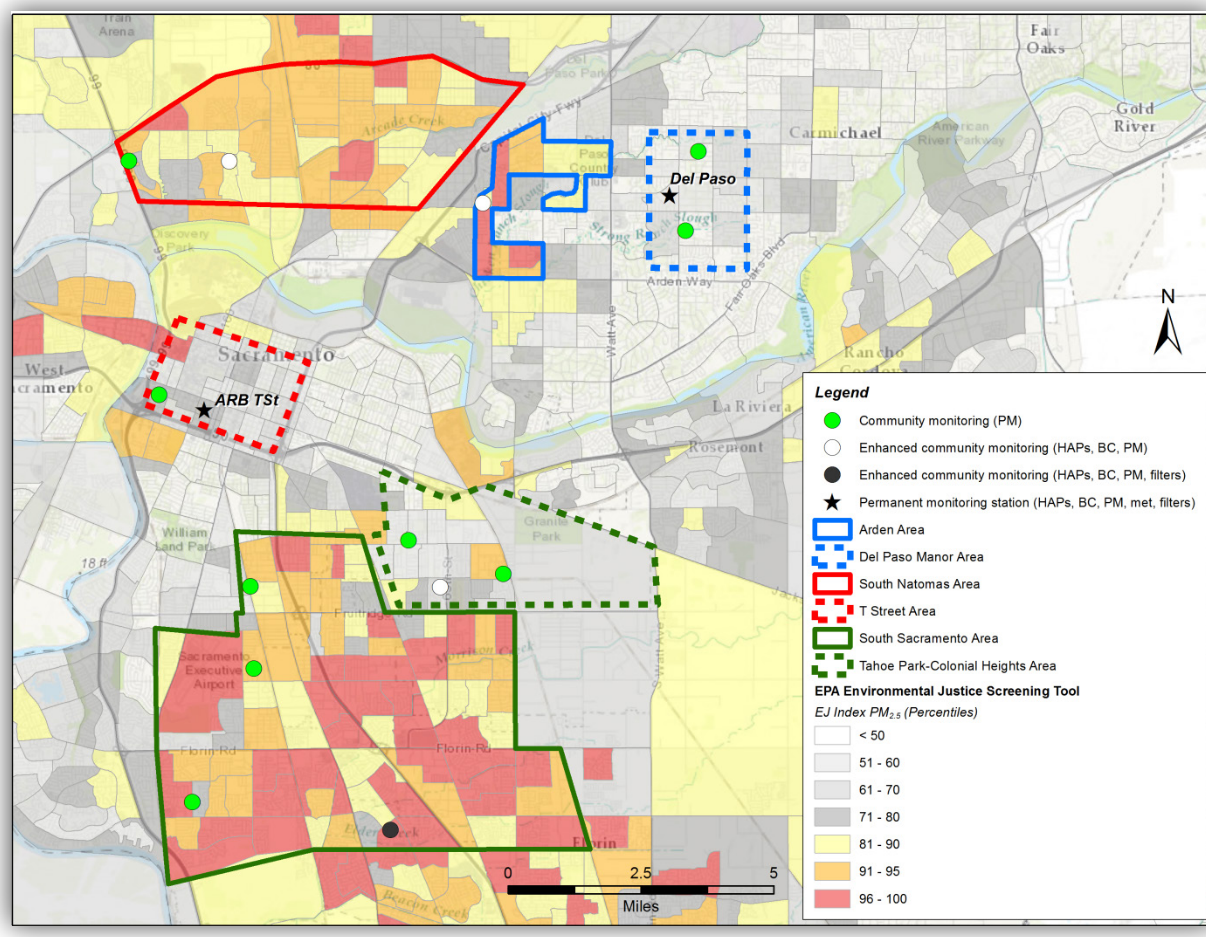


Figure 1. The Sacramento communities where monitoring was conducted, the monitoring locations, and the EJ Index for $PM_{2.5}$, which is based on EPA's Environmental Justice screening tool (see Section 2).

This was the first study in Sacramento to examine the contribution of wood burning to air toxics. This analysis helps SMAQMD staff understand air toxics concentrations between EJ and non-EJ communities, and the contribution of wood smoke and other sources to ambient air toxics concentrations. Air pollution data were combined with phone survey results on wood burning practices (see Appendix A); together, pollution gradients and survey information were assessed to improve the understanding of relative air toxics concentrations between EJ and non-EJ communities.

2. Methods

2.1 Site Selection

The measurement program for this study was designed to measure HAPs, wood smoke, and PM in three EJ and three non-EJ communities. Each EJ community was paired with a non-EJ community for comparison. Three tiers of sites were used:

1. **Tier 1 locations** – heavily instrumented sites at the two existing Sacramento air monitoring sites—T Street and Del Paso Manor—located in non-EJ communities.
2. **Tier 2 locations** – moderately instrumented sites located in three EJ communities and one non-EJ community.
3. **Tier 3 locations** – low-cost AirBeam PM sensors at one to three locations in each EJ and non-EJ community.

EPA's EJScreen tool[1] was used to identify EJ communities that could be paired with the Del Paso Manor and T Street. For this study, EJ communities were defined as those in the highest 10th percentile EJ Index for $PM_{2.5}$. The Arden community (EJ) was paired with Del Paso Manor (non-EJ), while the South Natomas community (EJ) was paired with T Street (non-EJ), since the sites in each pair pairs are relatively close to each other. South Sacramento was selected as an additional EJ community, because there is limited air quality monitoring in the area and the community had multiple census blocks with an EJ Index for $PM_{2.5}$ in the top 10% of the nation. The nearby community of Colonial Heights was selected as the remaining non-EJ community. Figure 1 shows the location of all the study sites.

After identifying the communities, SMAQMD conducted public outreach through local community groups, and its Board Members and staff, in a search for volunteers to host the monitoring equipment. Within the boundaries of interest were not pursued further. Sites in the three EJ communities were required to be in a census block with an EJ Index for $PM_{2.5}$ in the top 10% of the nation. Potential sites were visited by STI and SMAQMD staff to assess their viability. Requirements for the sites included ease of access, area safety, sufficient privacy so that the monitoring equipment was not easily noticeable from nearby streets or alleys, and sufficient space to place monitoring equipment. **Table 1** lists the sites by tiers.

[1] Data retrieved July 2017 from https://ejscreen.epa.gov/mapper.

Table 1. Study sites by tier.

Tier	Site Names
1	Del Paso Manor, T Street
2	64th Street, Darwin, Soccoro, Tristan
3	13th Avenue, 24th Avenue, 79th Street, Alderwood, Coroval, Henrietta, Hermosa, Wyman, T Street Tier 3

2.2 Study Design

This section describes the approach to study design that was taken to address the research questions posed and to meet the data quality objectives outlined in the Quality Assurance Project Plan (QAPP). A combination of measurement techniques was used in this study to quantify ambient air toxics concentrations and wood burning contributions in multiple communities with high precision.

Table 2 details the types of measurements conducted, and Table 3 lists the measurements conducted by tier. To quantify HAPs, Summa stainless steel canisters were collected at Tier 1 and Tier 2 sites, and analyzed for selected HAPs using EPA's TO-15 analytical sample method (Swift et al., 2007; U.S. Environmental Protection Agency, 1999). To quantify wood smoke, Magee Scientific Aethalometers (Model AE33) were deployed at the same sites with canisters. Aethalometer BC data were separated into BC from wood burning (BC_{wb}) and from fossil fuel combustion (BC_{ff}). Quartz fiber filters were collected from the Del Paso Manor, T Street, and South Sacramento sites at roughly the same time as canister samples, and analyzed for levoglucosan (a tracer for wood smoke), and organic and elemental carbon (OC, EC). At all sites, AirBeam low-cost sensors were used to quantify PM. Additional methodology information is discussed in Section 2.6.4. HAPs canister and PM filter samples were set up for collection when $PM_{2.5}$ concentrations were forecasted to be high.

A combination of continuous and filter- or canister-based measurements provided cost-effective spatial and temporal coverage of the pollutants of concern. Twelve-hour daytime and nighttime filter and canister samples were taken to isolate daytime versus nighttime emissions. Mobile source emissions are relatively higher in the daytime compared to nighttime, and residential wood burning emissions are higher in nighttime compared to daytime (Allen et al., 2011; Crilley et al., 2015).

In parallel with the ambient measurements, a phone survey was conducted to characterize what indoor burning devices are used and how often people burn with these devices in the EJ and non-EJ communities where the ambient sampling occurred. Data from the ambient measurements and survey were then compared; see Section 2.7 for details of the phone survey method.

Table 2. Measurements conducted during the study period of December 1, 2016, through January 31, 2017.

Pollutant	Collection Method(s)	Time Resolution	Frequency
$PM_{2.5}$	1. AirBeam sensors 2. Met One Beta Attenuation Monitor (BAM) 1020 3. Federal reference method (FRM) R&P 2025 sequential filter sampler	1. 1 minute 2. Hourly 3. Daily	Continuously
Gaseous HAPs	Canister sampler TO-15 analysis	12-hour	Episodic
1. BC_{ff} 2. BC_{wb}	1. Aethalometer 2. Levoglucosan from filters	Hourly	Continuously
Levoglucosan, OC, and EC	Filters collected with mini-vol or Thermo 2025i filter sampler	12-hour	Episodic, coincident with canister samples
Surface meteorology (wind speed and wind direction)	R.M. Young systems	Hourly	Continuously

Table 3. Pollutants measured by tier.

Pollutant	Tier 1	Tier 2	Tier 3
FRM $PM_{2.5}$	X		
BAM $PM_{2.5}$	X		
AirBeam PM	X	X	X
Gaseous HAPs	X	X	
BC_{ff} and BC_{wb}	X	X	
Levoglucosan, OC, and EC	X	Tristan site only, to collect samples in south Sacramento	

Figures 2 through 5 show site photos for Del Paso Manor (where pre- and post-study AirBeam collocations occurred), T Street, Henrietta (solar site example), and Alderwood (non-solar site example).

Figure 2. The Del Paso Manor site during collocation.

Figure 3. The T Street site.

Figure 4. The Henrietta site.

Figure 5. The Alderwood site.

2.3 Data Validation

This section summarizes how the data collected during the study compared to the goals set in the QAPP. Table 4 details the data quality indicator goals for each instrument; additional details are provided in the project quality assurance project plan (Hafner et al., 2016). Nearly all data quality goals were met, and data completeness objectives were met for each instrument. Goals that were not met were that the AirBeam data were not consistently within 30% of the collocated BAM data, and acrolein data did not meet the goal of ±30% precision for collocated samples.

Table 4. Data quality indicator goals.

Instrument	Assessment	Criteria
AirBeam	(1) Sensitivity (2) Sticking check (3) Temperature check (4) RH check (5) Data completeness (6) Accuracy (7) Precision	(1) 1-400 µg/m^3; ±1 µg/m^3 (2) >3 hours (3) Temperature outside range of 32° to 122°F (4) RH >95% (5) 75% completeness (by hour and hours in day) (6) Calibrated values are ±30% of BAM measurements (7) ±20% for collocated measurements
Aethalometer	(1) Flow check (2) Data completeness (3) Sensitivity	(1) ±10% of 5 liters per minute (LPM) (2) 75% completeness (by hour and hours in day) (3) 0.01 – 100 µg/m^3, ±0.001 µg/m^3
Canister Samples	(1) Flow check (2) Collocated samples (3) Audit accuracy (4) Replicate precision (5) Completeness (6) Sensitivity	(1) ±10% (2) ±30% (for concentrations >5 x MDL) (3) ±30% (4) ±30% (5) ±1 hour of target sample duration; 75% valid samples (6) Meet MDLs specified in the laboratory SOP
Filter samples	(1) Flow check (2) Collocated samples (3) Replicate precision (4) Field blanks (5) Completeness (6) Sensitivity	(1) ±10% (2) ±30% (3) ±10% (4) At or below MDLs for target compounds (5) ±1 hour of target sample duration; 75% valid samples (6) Meet MDLs promised by the laboratory

AirBeam – The accuracy, precision, data completeness, and sensitivity goals for the AirBeam sensors were met. The AirBeams had very high precision, with collocated data having an r^2 value of greater than 0.95. Data were visually reviewed daily during the study, and periods when data from a given AirBeam were near zero and noisy while all other AirBeams reported higher concentrations were deemed invalid. The AirBeam data were not consistently within 30% of the collocated BAM data. However, because AirBeam precision was high, inter-community differences could be determined with confidence.

Aethalometer – Aethalometer data were visually inspected at the 1-minute and 1-hour levels for all channels for large and unusual spikes that coincided with tape advances, instrument noise, and shifts in baseline. Periods where there was a very large (greater than 50 $\mu g/m^3$) spike in one channel but not in others were invalidated. Periods of instrument noise at the Tristan and T Street sites, when moisture got into the sampling line, were invalidated.

Canister and Filter Samples – For volatile organic compounds (VOCs), data were visually inspected upon receipt from the laboratory and reviewed to ensure that detection limits were met, internal standard recovery was sufficient, and precision goals were met. Acrolein data did not meet the ±30% precision goal for collocated samples; this is consistent with other studies showing difficulties with acrolein.[2] Filter sample results were reviewed for correct calibrations and calculations from the raw chromatograph data, relationships between levoglucosan and organic carbon, and precision.

2.4 Analytical Methods

2.4.1 HAPs Sampling and Laboratory Analysis

HAPs were collected at the Tier 1 and Tier 2 sites (six sites in total) using five liter Summa stainless steel canisters at each site. Samples were collected for four sequential 12-hour durations starting at either 6 a.m. or 6 p.m. PST on a forecast basis from December 1, 2016, through January 31, 2017. Daytime and nighttime samples were taken, since sources are different in daytime and nighttime. Mobile source emissions are relatively higher in daytime, and residential wood burning emissions are higher in nighttime (Allen et al., 2011; Crilley et al., 2015; Favez O. et al., 2009). Thus, a comparison of daytime to nighttime concentrations can show which source type contributes more to ambient HAPs.

STI generates same- and next-day air quality forecasts for SMAQMD. When forecasts indicated that $PM_{2.5}$ concentrations would be high on a particular day, samples were taken later in the evening or on the next day. Thus, samples were usually collected on an intensive basis, with four to eight samples collected over a 2- to 4-day period; sample periods were December 19-23, December 29-30, January 15-17, and January 27-30, periods when $PM_{2.5}$ was forecast to be high. Ten collocated samples were collected at the T Street site. In addition, at the Del Paso Manor site, five 12-hr samples were collected on November 9-11, 2016, to characterize HAP concentrations prior to the wood

[2] https://www3.epa.gov/ttnamti1/files/2009conference/Acrolein.pdf

burning season. Table 5 shows the number of samples collected at each site; 140 samples were collected during the study.

Table 5. Canister sample collection totals and the start and end times of sampling at each of the six sites.

Site Name	Number of 12-hr HAPs Samples	First Sample (Start Time, PST)	Last Sample (Start Time, PST)
ARB T Street	12, 10 of which had 2 collocated samples taken	12/19/2016 18:00	2/1/2017 6:00
64th Street	23	12/19/2016 18:00	2/1/2017 18:00
Darwin	23	12/19/2016 18:00	2/1/2017 18:00
Socorro	24	12/19/2016 18:00	2/1/2017 18:00
Tristan	24	12/19/2016 18:00	2/1/2017 18:00
Del Paso Manor	33	11/9/2016 18:00	2/2/2017 6:00

Canisters were shipped to Eastern Research Group (ERG) for analysis by EPA Method TO-15[3] using a gas chromatography-mass spectroscopy (GC-MS) system. Gaseous target compounds included 1,3-butadiene, 2,2,4-trimethylpentane (also called iso-octane), acetonitrile, acetylene, acrolein, acrylonitrile, benzene, carbon tetrachloride, ethylbenzene, m-xylene, p-xylene, and toluene. These key hydrocarbons are among the highest contributors to cancer risk and hazard nationally (McCarthy et al., 2009; U.S. Environmental Protection Agency, 2015a). In addition, many are found in wood smoke (Lee et al., 2005; Naeher et al., 2007; Gustafson et al., 2007) and were targeted to examine the potential impact of wood smoke on local concentrations of air toxics. 2,2,4-trimethylpentane is used as the tracer for fossil fuel combustion, and is not from wood smoke (McCarthy et al., 2013).

Method detection limits (MDLs) were unique to each canister. Each sample concentration was compared to sample-specific MDL.

Table 6 lists the median method detection limits (MDLs) achieved for this study. Acrylonitrile was never detected in any samples at those detection limits, while all other target compounds were above detection limits in more than 95% of samples. Detection limits were typically below 30 parts per trillion (ppt) for most target HAPs compounds.

[3] https://www3.epa.gov/ttnamti1/files/ambient/airtox/to-15r.pdf

Table 6. Median method detection limits for HAPs during this study in parts per billion (ppb).

Analyte	MDL
1,3-Butadiene	0.026
2,2,4-Trimethylpentane	0.0098
Acetonitrile	0.051
Acetylene	0.029
Acrolein	0.12
Acrylonitrile	0.03
Benzene	0.021
Carbon Tetrachloride	0.016
Ethylbenzene	0.019
m,p-Xylene	0.04
Toluene	0.017

HAP data were assessed to examine differences in concentrations spatially and temporally. HAPs data were also compared to levoglucosan, $PM_{2.5}$, and BC data to assess whether there were any covariates that would indicate similar emissions sources. Meteorological conditions on sample days are summarized in Table 7. Average RH for all HAP collection periods ranged from 68% to 95%, with an average of 82%. All nighttime sample periods when HAPs samples were collected had an average humidity greater than or equal to 80%, while daytime samples for HAPs generally had lower RH, higher temperatures, and higher wind speeds. Very little precipitation occurred during HAP canister sampling periods. During the overall study period, including the HAP collection periods, relative humidity values were quite high; RH was 85% or greater during 65% of the measurement hours, and 90% or greater during 57% of the hours.

Table 7. Average meteorological conditions at Del Paso Manor and T Street during 12-hr canister sampling periods.

Sampling Period Start Time (PST)	Wind Speed (m/s)	Temperature (°C)	RH (%)	Total Precipitation (mm)	Number of Samples
12/19/2016 18:00	0.4	3.7	87	0	6
12/20/2016 06:00	1.8	8.6	68	0	6
12/20/2016 18:00	0.7	6.8	82	0	5
12/21/2016 06:00	1.3	10.7	68	0	6
12/21/2016 18:00	0.6	6.1	93	0	1
12/22/2016 06:00	1.3	10.3	71	0	5
12/22/2016 18:00	2.9	9.4	80	0	5
12/23/2016 06:00	5.9	9.2	91	4.96	5
12/23/2016 18:00	1.4	4.9	94	0	5
12/29/2016 06:00	1.6	9.3	73	0	6
12/29/2016 18:00	0.5	5.8	92	0	5
12/30/2016 06:00	2.5	9.2	78	0	6
12/30/2016 18:00	3.1	8.5	87	0	4
1/15/2017 18:00	0.7	5.3	92	0	5
1/16/2017 06:00	2.3	8.1	76	0	6
1/16/2017 18:00	1.1	4.4	91	0	5
1/17/2017 06:00	2.5	4.9	92	0	6
1/27/2017 18:00	0.4	5.2	91	0	1
1/28/2017 06:00	1.6	9.7	70	0	1
1/28/2017 18:00	0.5	6.4	87	0	6
1/29/2017 06:00	1.7	10.7	68	0	5
1/29/2017 18:00	0.5	6.9	85	0	6
1/30/2017 06:00	1.4	11.1	69	0	5
1/30/2017 18:00	0.4	8.8	90	0	1

2.4.2 Filter Collection and Laboratory Analysis for Levoglucosan

Quartz fiber filters (47 mm, Pall Life Sciences) were collected at Del Paso Manor, T Street, and Tristan sites on a forecast basis, generally at the same time as the nighttime HAPs samples (i.e., 18:00 to 06:00 PST). Filters were analyzed for OC, EC, and levoglucosan. Levoglucosan was used as the main tracer for wood burning emissions. Levoglucosan is emitted during combustion of wood cellulose (Simoneit et al., 1999), and its emissions, relative to total emitted PM, can vary by fuel type and burning condition (Sullivan et al., 2008). Levoglucosan may be oxidized in the atmosphere (Hennigan et al., 2011; 2010), but is relatively stable compared to other co-emitted compounds and is emitted in relative abundance from biomass burning, making it a commonly used tracer (Fraser and Lakshmanan, 2000; Hoffmann et al., 2010).

Two daytime (06:00 to 18:00 PST) filters were also collected at each site during January 2017 to evaluate the difference between daytime and nighttime wood smoke concentrations, since residential wood smoke emissions generally occur at night. At the Del Paso Manor and T Street sites, Thermo Scientific 2025i sequential filtration samplers were used, with a sampling rate of 16.7 L/min. At the Tristan site, an AirMetrics mini-vol sampler was used, with a sampling rate of 5 L/min; a sufficient sample was collected at all sites for lab analysis, so the lower flow rate should not have impacted results. Sample flow was evaluated prior to and after each sampling event. Five collocated filters were collected at Tristan to evaluate precision. Prior to sampling, filters were pre-baked for 12 hours at 500°C to remove residual organics.

Levoglucosan analysis was performed by Dr. Amy Sullivan at Colorado State University on a Dionex DX-500 series ion chromatograph, with detection via an ED-50/ED-50A electrochemical cell. This cell includes two electrodes: a pH-Ag/AgCl (silver/silver chloride) reference electrode, and a “standard” gold working electrode. For the separation, a sodium hydroxide gradient and a Dionex CarboPac PA-1 column (4 x 250 mm) were used. The complete run time was 59 minutes, with an injection volume of 100 mL. More details on the method can be found in Sullivan et al. (2011a; 2011b; 2014).

2.5 Continuous Instrumentation

2.5.1 Aethalometer Operations and Data for Black Carbon

Six Magee Scientific Aethalometers model AE33 were deployed at the Tier 1 and Tier 2 sites to measure BC. The AE33 collects ambient aerosol onto a filter tape, and then every five minutes, measures the absorbance of the material deposited on the tape at 7 wavelengths, ranging from 370 to 960 nm. The BC concentration is from the 880 nm channel. While BC absorbs uniformly across all wavelengths at which absorbance is measured, brown carbon, which is produced by combustion of wood or other biomass, absorbs primarily in the lower wavelengths of the measured range (Park et al., 2006; Jeong et al., 2004). A commonly used method is to assume that BC is only from wood burning and fossil fuel combustion, so that the difference in absorbance at the 470 nm and 960 nm wavelengths can be used to calculate the quantity of BC_{wb} and BC_{ff}. This method assumes that there are no other sources of BC, such as coal dust. In the Sacramento emissions inventory, there is little to no impact from coal combustion emissions, so mobile sources and wood burning emissions are the main sources of LAC.

To calculate BC_{wb} and BC_{ff}, the model described by Sandradewi et al. (2008a) and summarized in the AE33 User Manual (Magee Scientific, 2016) was used. The method uses the concentration values calculated using the 470 nm and 960 nm wavelengths to estimate the percentage of BC from wood burning. Concentrations of BC_{wb} and BC_{ff} are then calculated by multiplying the BC value from the 880 nm channel by the percentages obtained in the previous step. The calculation is based on a model in which the total BC can be divided into pure black and pure brown carbon using the spectral dependence of the absorbing properties of each material. The spectral dependence is described by the Angstrom exponent (α). From the Beer-Lambert Law, the following equations can be obtained:

$$\frac{b_{abs}(470\ nm)_{ff}}{b_{abs}(950\ nm)_{ff}} = \left(\frac{470}{950}\right)^{-\alpha_{ff}}$$

$$\frac{b_{abs}(470\ nm)_{wb}}{b_{abs}(950\ nm)_{wb}} = \left(\frac{470}{950}\right)^{-\alpha_{wb}}$$

$$b_{abs}(\lambda) = b_{abs}(\lambda)_{ff} + b_{abs}(\lambda)_{wb}$$

Where $b_{abs}(\lambda)_x$ is the absorption coefficient for the species times (wb or ff) at wavelength λ (470 or 950).

The Sandradewi method requires input values for the Angstrom exponents for pure black and pure brown carbon. For this study, a value of 1 for the pure black carbon Angstrom exponent and a value of 2 for the pure brown carbon Angstrom exponent was used. These are the default values used by the Aethalometer (Drinovec et al., 2015; Magee Scientific, 2016) and have been widely used in the scientific literature (Crilley et al., 2015). Harrison et al. (2013) points out that use of the Aethalometer model can have limitations, notably from uncertainty in the Angstrom exponent selected for wood smoke, and when other sources of BC aerosol impacting a monitor, such as coal emissions.

2.5.2 $PM_{2.5}$ Sensor Methods

The $PM_{2.5}$ sensor model used in this study is the AirBeam (**Figure 6**), available at roughly $250 USD, which was developed by HabitatMap Inc., Brooklyn, New York, to measure $PM_{2.5}$ using an optical technique. HabitatMap developed the AirBeam on an open source platform, and the schematics of the instrument and default firmware are available online.[4] A Shinyei PPD60PV-T2 sensor unit provides a light-emitting diode (LED) source of visible green light to detect particles less than 2.5 µm and greater than 0.5 µm in diameter, and the raw measurement provides total particle counts. This particle count is then converted to mass concentration, using the manufacturer default size distribution of ambient $PM_{2.5}$ and constant particle density. The default retrieval algorithm used in the study is

[4] http://aircasting.org/about

$PM_{2.5}$ ($\mu g \cdot m^{-3}$) = 0.518 + 0.00274 × particle count (hppcf), where hppcf is hundreds of particles per cubic foot The firmware used for the duration of this study was version 11_14_15.

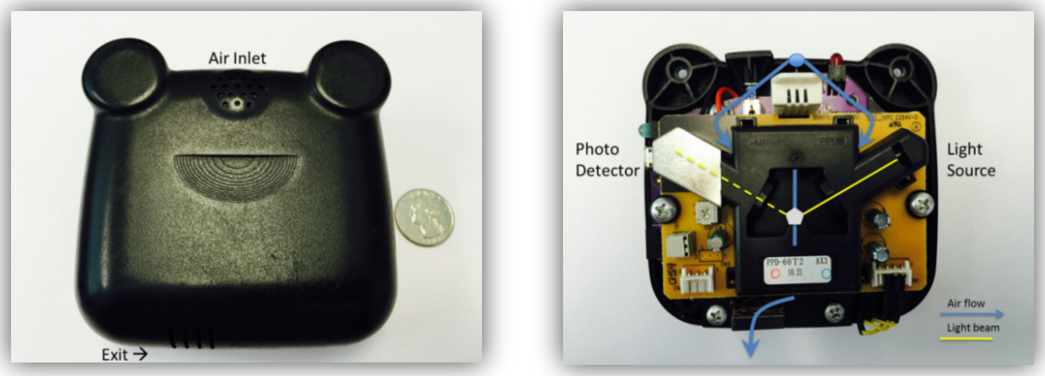


Figure 6. Internal components of the AirBeam sensor.

In previous studies, the AirBeam was shown to demonstrate high sensor-to-sensor precision in the environments of Decatur, Georgia, and Cuyama Valley, California (Jiao et al., 2016; Mukherjee et al., 2017). These studies also examined the performance of the AirBeam relative to reference regulatory monitors, and showed that meteorological variables such as RH and wind speed had predictive capacity with regard to the deviation between the AirBeam and reference instruments. The Air Quality Sensor Performance Evaluation Center (AQ-SPEC)[5] has assessed the AirBeam and multiple other sensors in laboratory and field conditions. In laboratory comparisons against the FEM GRIMM, the AirBeam sensors showed good correlation (Pearson coefficient of determination [R^2] ~0.87) at 5-minute resolution, while underestimating $PM_{2.5}$ mass by around a factor of five. Similar results were demonstrated in the field, and raw particle counts had better agreement between the two instruments than retrieved $PM_{2.5}$ concentrations. AQ-SPEC assessments also show that the AirBeam has high precision over a range of temperature and RH conditions. An EPA study examined the performance of the AirBeam compared to the BAM and found high precision and moderate accuracy (Jiao et al., 2016). These results were obtained prior to the November 2015 firmware update that was used for the duration of this study.

For this application, AirBeams were mounted on tripods covered in a metal hood to keep rain off but so as to not obstruct air flow. AirBeams have Bluetooth technology to transfer data from the sensor to a handheld smart device or data storage location. Due to the limited range of the Bluetooth signal (5 to 10 feet), AirBeams used in the study were configured with Valarm serial adaptors and wireless cellular network components to send data in real-time (1-minute averages) from the AirBeam to Valarm's data cloud, which was then retrieved for data collection and storage. Valarm's Yoctopuce Yocto serial sensor adaptors were connected to the AirBeam's auxiliary ports via single-pin wires, which gathered data from the AirBeam for delivery. Valarm's GSM 3G sensor hub was connected to the serial adaptor via micro-USB, and the hub was outfitted with a Ting GSM SIM card, which transmitted data to Valarm's cloud.

[5] http://www.aqmd.gov/aq-spec

Two different methods were used to power the AirBeam units used in the study: hardwired AC power, and a solar and battery power combination. Both methods provide sufficient power to the AirBeam, so there is no difference in measurements from the AirBeam due to the power source. The power method for each AirBeam monitoring unit was determined on a site-by-site basis depending on availability of power resources. If the hosting site contained an accessible outdoor power outlet (and permission from the owner was given), a heavy-duty outdoor-rated extension cable was installed inside the AirBeam's utility box as a direct power source. A majority of the AirBeam monitoring units used this power method. If the hosting site did not have an accessible outdoor power outlet, a solar/battery power configuration was used. Due to the limited power needs of an AirBeam monitoring unit, a 12-volt outdoor marine-grade deep cycle battery was wired to the AirBeam's utility box and served as the main power source for the unit. Inside the AirBeam's utility box, a Valarm 12-volt DC power regulator with a micro-USB port was wired to the battery cables and served as a platform to connect the AirBeam and data communication components. In addition to the battery, a solar panel was mounted to the top of the AirBeam's monitoring unit, and was wired into the battery's wiring harness with a solar controller regulator to charge the battery. The AirBeams and Valarm data communication components connected to a power source via USB. Both of these power methods yielded a connection for a multi-port USB adaptor, enabling a power source for all devices.

Data were reviewed daily in real time during the study. One-minute AirBeam sensor data were averaged to hourly values and required 75% completeness for each hour. After the study, the time series data were visually inspected to identify and remove any periods where sensor response degraded. For a few days at T Street Tier 3 and at 79th St., the battery provided insufficient power to the sensor, resulting in a low, relatively invariant signal.

2.5.3 $PM_{2.5}$ and Meteorological Measurements at the Del Paso Manor and T Street Sites (Tier 1 Sites)

Hourly $PM_{2.5}$ mass and meteorological data were obtained from existing sites; the Del Paso Manor site (maintained by SMAQMD) and the T Street site (maintained by ARB). The Del Paso Manor site was located at 2701 Avalon Drive, and the T Street site was located at 1309 T Street. At both sites, a BAM 1020 collected hourly $PM_{2.5}$ data, and an R&P 2025 sequential filter sampler was operated as the 24-hr FRM for $PM_{2.5}$ mass. FRM filters are collected daily, and $PM_{2.5}$ mass was determined by gravimetric analysis. Temperature, RH, wind speed, and wind direction data were collected at both sites using R.M. Young instrumentation. Based on temperature and RH measurements, dew point was also calculated. Instrumentation and operations at these sites followed national guidance set by EPA on operations and methods.

Wind and temperature data were used for the analysis of BC data. Each site with Aethalometer and canister measurements was assigned meteorological data from the weather station closest to that monitoring site (Table 8).

Table 8. Weather station data used to assign meteorological data to the AE33 monitor sites; distance (km) between the monitor and weather station.

Weather Station	Monitor Sites
Del Paso Manor	Del Paso Manor (0 km), Darwin (4.4 km)
T Street	T Street (0 km), 64th Street (6.9 km), Socorro (5.8 km), Tristan (10.9 km)

2.6 Data Analysis Methods

2.6.1 Statistical Methods

Statistical methods for our data analysis included conditional bivariate probability function plots (Carslaw and Ropkins, 2012; Uria-Tellaetxe and Carslaw, 2014), notched box whisker plots, coefficient of divergence calculations, ratio:ratio plots, and Kruskal-Wallis rank sum tests. Unless otherwise noted, the term "significant" is used when the p-value of Student's T-test is less than 0.05.

Data were also compared to the 4-km emissions inventory (EI), and source apportionment was performed using EPA's positive matrix factorization (PMF) model.

Community Comparison

To determine whether significant differences in measured concentrations of BC, BC_{ff}, and BC_{wb} existed across communities, a Kruskal-Wallis rank sum test was performed on HAPs concentrations among the communities. The Kruskal-Wallis test was selected to assess how similar the distribution of data is among sites. Posthoc Nemenyi-tests were applied for pairwise comparisons on BC data between each community to determine which communities' measurements differed significantly from each other; this test is useful for determining whether multiple groups of data are similar or not when there is a large amount of data (Tzima et al., 2011).

Bivariate CPF Methods

To identify potential sources of black carbon, a conditional bivariate probability function (CBPF) analysis (Uria-Tellaetxe and Carslaw, 2014) was used. CBPF is similar to conditional probability function (CPF) analysis, which is commonly used to identify emissions sources. In CPF analysis, wind direction sectors that have a high probability of pollutant concentrations greater than a selected percentile of the total data are identified. CBPF enhances this method by incorporating wind speed bins and wind direction into the analysis. Specifically, where m is the number of samples with a concentration greater than the specified percentile, n is the total number of samples, θ is a wind direction sector, and j is the wind speed interval, the following equation is used to determine CBPF.

$$CBPF = \frac{m_{\theta,j}}{n_{\theta,j}}$$

CBPF is able to determine whether certain combinations of wind speed and wind direction have a high probability of producing concentrations above the specified percentile of data. By providing a greater degree of granularity to the analysis, CBPF facilitates the identification of sources that might not be detected by traditional CPF, and can also be used to evaluate the characteristics of a source.

The polarPlot function available in the openair R package (Carslaw and Ropkins, 2012; Grange et al., 2016) was used to perform our CBPF analysis. CBPF analyses were done for each site where an AE33 was deployed to collect BC, BC_{wb}, and BC_{ff} concentrations, based on the 80th percentile of the concentrations of each pollutant. The calculations, including the 80th percentile threshold, were performed individually for each site, and radial plots displaying the probability of exceeding the 80th percentile relative to wind speed and direction were created.

Coefficient of Divergence

The Coefficient of Divergence (COD) was calculated for HAPs, PM, and BC as:

$$\mathrm{COD}_j^{i,k} = \sqrt{\frac{1}{p_j^{i,k}} \sum_{t(j \in i,k)}^{p_j^{i,k}} \left(\frac{x_{t,j}^i - x_{t,j}^k}{x_{t,j}^i + x_{t,j}^k} \right)^2}$$

where $x^i_{t,j}$ is the concentration of parameter *j* on day *t* at monitor *i*, $x^k_{t,j}$ is the concentration of parameter *j* on day *t* at monitor *k*, and $p_j^{i,k}$ represents the number of days with data for parameter *j* for both monitors *i* and *k*. COD indicates the spatial variability of concentrations across multiple monitors (Wilson et al., 2005; Wongphatarakul et al., 1998), so identification of which pollutants are community-, urban-, or regional-scale. COD are lower at monitoring sites where concentrations are regionally driven, and higher when there are more localized sources. In the air quality context, researchers typically use a COD of greater than 0.2 to indicate modest heterogeneity (Wilson et al., 2005; Tilgner et al., 2014; Yadav and Turner, 2014). BC typically has higher inter-site COD values than $PM_{2.5}$. For example, Wang et al. (2011) found COD values for BC ranging from 0.08 to 0.46 across 12 sites in Rochester, New York, while Zikova et al. (2017) reports COD values in Rochester of 0.2 for daily PM and 0.36 for hourly data.

Ratio:Ratio Plots

Ratio:ratio plots were used to assess how individual species relationships changed as a function of known tracers of wood smoke (BC_{wb}) and fossil fuel use (2,2,4-trimethylpentane, also known as iso-octane) (McCarthy et al., 2013). In a ratio:ratio plot, the ratio of two species is plotted on both the x- and y-axis. Every possible combination of the 12-hr HAPs samples were plotted against each other, relative to either BC_{wb} or 2,2,4-trimethylpentane; only examples are shown in Section 3.5.2. If the shape of the relationship changes when compared to when a tracer is used as the denominator, it can indicate alternate emissions sources are affecting concentrations of one of the two species at a given site (Subramanian et al., 2006).

2.6.2 Comparison to Emissions Inventory Data

As part of this work, data from the winter $PM_{2.5}$ emissions inventory for the study area were compared to the measurements, to assess how well the inventory represents ambient concentrations. Sacramento provided 2012 emissions inventory (EI) data for weekdays and weekends in the winter season on a 4-by-4 km grid to ARB's California Emissions Projection Analysis Model (CEPAM): External Adjustment Reporting Tool. The inventory provides $PM_{2.5}$ emissions data in tons emitted per year, divided by the total number of days in the year, in each grid cell. These grid cell values were then compared to the average of all AirBeam values in that grid cell. For each AirBeam, the average $PM_{2.5}$ concentration for the study period was calculated from hourly values; only data points collected at times when data were available from all AirBeam sites were used to calculate the averages. The average of all AirBeam measurements falling in a single EI grid was then calculated. A linear regression equation was fit for the average PM measurement and the EI data, and the R^2 was calculated for the regression.

2.6.3 Source Attribution with Positive Matrix Factorization

The PMF model was used to separate out contributions from biomass burning to the HAPs. Such multivariate receptor modeling tools are widely used for examining patterns in environmental data. PMF is a widely used model and data analysis tool that decomposes a matrix of speciated sample data into two matrices—factor contributions and factor profiles—in order to understand the factors or sources impacting the speciated sample data. The PMF methods are summarized below, and details are provided in Brown et al. (2015) and Paatero et al. (1997; 2014).

A speciated data set can be viewed as a data matrix X with dimensions *n* by *m*, in which *n* samples and *m* chemical species were measured. Rows and columns of X are indexed by *i*, and related matrices are indexed by *j*. The goal of multivariate receptor modeling—for example, with PMF—is to identify the number of factors (*p*), the species profile of each factor (*f*), and the amount of mass contributed by each factor (*g*) to each individual sample that solves the chemical mass balance between measured species concentrations and factor profiles. The equation used is

$$x_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij}$$

where e_{ij} is the residual for each sample/species, and c_{ij} is the modeled solution of x_{ij}. Entire matrices are denoted by capital bold-face letters. Columns of the factor contribution matrix **G** may be denoted by g_k, and similarly, rows of factor profile matrix **F** may be denoted by f_k.

In PMF, factor elements are constrained so that no sample can have a significantly negative contribution. PMF allows each data value to be individually weighted. This feature allows adjustments on the influence of each data point, depending on the confidence in the measurement. The PMF solution minimizes the object function *Q* via a conjugate gradient algorithm, based upon the estimated data uncertainties (or adjusted data uncertainties), represented by u_{ij}.

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[\frac{x_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}}{u_{ij}} \right]^2$$

Typical procedures in the literature (Brown et al., 2015; Norris et al., 2014) were used, as follows. Uncertainties were calculated through the equation *(detection limit x 0.5) + (0.15 x average concentration)*. The lower limit of normalized factor contributions was the default -0.2, and robust mode and random seed values were used. To assess uncertainty, bootstrapping over 400 runs with a block size of 6 and R^2 of 0.8 was used; block size is calculated by EPA PMF, and the other settings follow literature guidance (Brown et al., 2015; Norris et al., 2014; Paatero et al., 2014). The input matrix included 115 samples and 11 species; species included the 10 HAPs that were routinely above detection, and BC_{wb}.

With PMF, sources of HAPs between wood burning, mobile sources, and any other identifiable sources can be separated. BC_{wb} is used as the tracer for wood burning, and iso-octane (2,2,4-trimethylpentane) is used as the tracer for mobile sources. Using these tracers, PMF factors can be ascribed to wood burning, mobile source, or other sources by the abundance of each of these tracers. Table 9 summarizes the species used in PMF and their signal/noise ratio (S/N); species with a higher S/N have more signal, and thus are more important when solving the PMF equation.

Table 9. PMF species and signal to noise ratios (S/N).

Species	S/N
Acetonitrile	1.88
Acetylene	5.38
Acrolein	1.65
BC_{wb}	2.84
Benzene	4.87
Carbon tetrachloride	3.11
Ethylbenzene	3.66
M,p-Xylene	4.02
Toluene	5.23
1,3-Butadiene	3.01
Iso-octane	4.87

2.6.4 Sensor Data Analysis Methods

A vital design element of this study was the collocation of the AirBeams with each other and the regulatory grade instruments, both at the beginning and ending of the study period. Collocation is vital to understand low-cost sensor accuracy and precision, identify potential signal drift, and provide confidence in the sensor data. The AirBeams were deployed in three distinct phases for the study:

1. **Pre-Study Collocation Period (Six days, 11/10/2016 – 11/16/2016)** – 19 AirBeams were collocated with a BAM 1020 and meteorology measurements at the Sacramento Del Paso Manor site;
2. **Study Period (2 Months, 12/1/2016 – 1/31/2017)** – 19 AirBeams were deployed at 15 monitoring sites in Sacramento. The Del Paso Manor and T Street sites each had three AirBeams collocated with a BAM 1020 and FRM monitor in order to assess sensor precision and drift during the study period. The remaining 13 AirBeams were deployed individually at the site locations shown in Figure 1.
3. **Post-Study Collocation Period (33 Days, 2/4/2017 – 3/8/2017)** – 19 AirBeams collocated with a BAM 1020 and meteorology measurements at the Del Paso Manor site in the same configuration as during the Pre-Study Collocation Period.

Studies have shown that factory default sensor response functions can have sensor-to-sensor offsets, which can be corrected for (Zikova et al., 2017). This correction can be developed from an independent reference instrument or from a set of sensors of the same model. In this study, the measurements from pre- and post-study collocation periods were used to develop the correction for each AirBeam, quantify precision (AirBeam versus AirBeam variability), and assess whether the response of individual AirBeams to ambient $PM_{2.5}$ concentrations drifted during the study. R^2 was calculated between each sensor, and the 19 sensor mean was calculated to understand precision and sensor-to-sensor variability. Linear regressions between each sensor and the mean of all 19 sensors were computed to calculate the correction needed for each sensor. The regressions for each sensor were compared for the pre- and post-study collocation periods to determine whether the offset of each sensor was stable and consistent during the study. These linear regressions were used to compute a correction factor for each sensor using the equation *Corrected AirBeam = (Raw AirBeam – Intercept)/Slope*. The correction ensures that when the sensors were deployed as a network during the study period, each sensor provided an intercomparable value. All data shown in the Results (Section 3) are corrected.

Collocated sensor measurements during the study period were used to examine precision. The degree of confidence in sensor precision is presented statistically as the standard deviation (SD) of the difference between the linear regression model and the true AirBeam value. Evaluating the precision during these periods provides quantification of how much of the variability from the study period was due to true varying aerosol conditions versus the impact of internal sensor-sensor variability.

The data from the collocation of sensors, BAM 1020s, and meteorological measurements at the Del Paso Manor and T Street sites during the study, were used to quantify drift, accuracy and the influence of meteorological conditions on the corrected AirBeam measurements. The relationship between corrected sensor measurements and BAM 1020 measurements was examined at the Del

Paso Manor site throughout the pre-study, study, and post-study periods to assess the stability of sensor measurements. The R^2 correlation between corrected sensors and BAM 1020 measurements was used to assess accuracy. Daily averages were taken to compare sensor measurements with FRM measurements and were used to compute correlation.

To investigate whether a spatial pattern was evident in the AirBeam $PM_{2.5}$ data, or if spatial variation could be attributed to random chance, the spatial autocorrelation of the average concentration measured by each AirBeam during the study was calculated using the Global Moran's I statistic. The statistic was calculated using the default parameter settings within the Spatial Autocorrelation (Morans I) tool in ArcGIS 10.5.

2.6.5 Filter Data Analysis

Multiple studies have examined how to best convert levoglucosan to total wood burning PM. Puxbaum et al. (2007) provided a review from numerous laboratory tests, and suggested using a factor of 7.35 to convert levoglucosan concentration to wood burning organic carbon concentrations for wood burning stoves in the United States, based on source profiles from Fine (2002). This is similar to what other studies have used (Gelencser et al., 2007; Pio et al., 2011; Brown et al., 2016), and is within the typical range used elsewhere; e.g., 10 in Szidat et al. (2009), and 11 in Fuller et al. (2014). In an extensive experiment in London, Crilley et al. (2015) compared multiple conversion factors, and found that the Puxbaum et al. (2007) factor of 7.35 gave the best agreement compared to a radiocarbon approach. Therefore the Puxbaum factor was used for calculations of wood burning PM concentrations from levoglucosan.

For each monitor site, a linear regression between BC_{wb} and levoglucosan was calculated. To do so, hourly BC_{wb} measurements over the 12-hour period during which filter measurements were collected were averaged together. A y-intercept of 0 was used, since BC_{wb} and levoglucosan are both from the same source and should thus trend together to zero (Fuller et al., 2014; Favez et al., 2010). The Pearson correlation coefficient for BC_{wb} and levoglucosan was calculated at each site. The site with the highest correlation coefficient between BC_{wb} and levoglucosan was used to develop the relationship between BC_{wb} and wood smoke $PM_{2.5}$.

2.7 Phone Survey Methods

During the study period of December 2016 through January 2017, Meta Research, Inc., conducted a phone survey of residents in the six communities where monitoring was conducted. Full details of the study report are provided in Appendix A. The objectives of the survey were to:

- Assess wood burning behavior
- Evaluate wood burning activity by type of device used to burn
- Compare wood burning activity between EJ and non-EJ communities

Telephone interviews were completed with 900 (444 EJ; 456 non-EJ) Sacramento County residents who owned a wood or pellet burning device (other than an outdoor barbecue) either inside or outside their home. The addresses in each community were provided by STI. These addresses were matched with listed landline and mobile phone numbers, then selected at random for interviewing.

The margin of error associated with a sample of 900 completed interviews is ±3.3% at the 95% confidence level. That is, there is a 95% chance that the true population parameters lie within 3.3% of the sample statistics. For example, if a response category to a question was chosen by 50% of sample respondents, there is a 95% chance that if the entire county population were surveyed, that same response category would be selected by 46.7%-53.3% of all residents (50% ±3.3%).

For the EJ community, with 444 completed interviews, the margin of error at the 95% confidence level is ±4.7%, while the non-EJ community, with 456 completed interviews, is ±4.6%. Table 10 summarizes the sample size and sampling error by community.

Most of the questions were asked in a closed-ended format, while some were asked open-ended and responses were categorized for quantitative analysis. Interviews took approximately 8 minutes on average to administer. Respondents were screened for age (18+) and ownership of a wood or pellet burning device, and to confirm residency in Sacramento County. Interviewing took place from December 2 through December 19, 2016, and from January 6 through January 22, 2017. Surveys were not conducted on holidays because response rates are typically lower on these days.

Table 10. Survey sample size and sampling error by community, and overall by EJ and non-EJ area.

	EJ		Non-EJ	
Neighborhood	**Sample Size**	**Sampling Error**	**Sample Size**	**Sampling Error**
Arden	44	14.8%	--	--
South Natomas	81	10.9%	--	--
South Sacramento	319	5.5%	--	--
Del Paso Manor	--	--	298	5.7%
T Street	--	--	30	17.9%
Colonial Heights	--	--	128	8.7%
Total	444	4.7%	456	4.6%

3. Results

3.1 HAPs

3.1.1 HAPs Precision Using Collocated Samples

Initial quality assurance of the data was performed by calculating the precision of the sampling and analytical methods. Ten collocated samples were collected at the ARB T Street site. Precision was calculated using the following formula, where A and B are the concentrations from the two collocated samples.

$$Precision\ (\%) = 200 \times |(A - B)| / (A+B)$$

The National Air Toxics Trends Stations (NATTS) goal for high precision data is +/- 15%. As shown in Table 11, median precision was lower than 15% for all pollutants except acrolein (40%) and acrylonitrile (all below detection). This information indicates that precision is sufficient to assess spatial variations of >15% for all pollutants except acrolein. Acrolein is known to have potential analytical issues based on canister sampling work done by Eastern Research Group Inc. and EPA[6].

Table 11. Collocated HAPs sample results.

Analyte	Emissions Sources	No. of Collocated Samples	Median Precision %	Average Precision %	Average Concentration (ppb)
2,2,4-Trimethylpentane (iso-octane)	Mobile source tracer	10	5.1	5.9	0.24
Acetylene	Mobile source tracer	10	5.3	6.2	2.48
Benzene	Air toxic	10	6.3	8.5	0.49
Carbon Tetrachloride	Air toxic; internal QC	10	5.8	8.5	0.09
Toluene	Combustion indicator	10	11.0	12.6	0.90
m,p-Xylene	Combustion indicator	10	9.4	14.0	0.48
Ethylbenzene	Air toxic	10	9.0	15.2	0.18
Acetonitrile	Air toxic	10	12.7	17.2	0.14

[6] https://www3.epa.gov/ttnamti1/files/2009conference/Acrolein.pdf

Analyte	Emissions Sources	No. of Collocated Samples	Median Precision %	Average Precision %	Average Concentration (ppb)
1,3-Butadiene	Air toxic	10	12.1	18.2	0.13
Acrolein	Air toxic	10	40.0	46.0	0.33
Acrylonitrile	Air toxic	10	<MDL	<MDL	<MDL

3.1.2 HAP Concentrations by Site

Concentrations of HAPs were often higher at EJ sites compared to non-EJ sites, significantly so for iso-octane, acrolein, benzene, ethylbenzene, m,p-xylene, and toluene ($p<0.05$). However, there is no significant difference between individual EJ/non-EJ site pairs (**Table 12**). The HAPs that are significantly higher at EJ areas are typically from mobile sources, including iso-octane, our indicator for mobile sources (McCarthy et al., 2013). Box plots showing concentrations by site and by EJ/non-EJ area are provided in **Appendix B**.

To put the HAP concentrations in context, average HAP concentrations were compared at the 6 sites in Sacramento to national ranges and health benchmarks (**Figure 7**). The national ranges are a 3-year average of wintertime samples (December through February). The Sacramento data are for the 20 samples collected in the December 2016 through January 2017 campaign, on days forecast to have high $PM_{2.5}$ concentrations. California Office of Environmental Health Hazard Assessment (OEHHA) health benchmarks for air toxics are also shown to demonstrate how concentrations in the Sacramento wintertime study compared to levels of concern. Chronic reference exposure level (REL) levels indicate non-cancer adverse effects. Cancer risk is the one-in-a-million cancer risk threshold for a 70-year exposure. This indicates a concentration level where cancer risk from a 70-year exposure to the chemical would likely result in one additional case of cancer per million people.

Overall, average concentrations of benzene, toluene, ethylbenzene, xylenes, 2,2,4-trimethylpentane, and 1,3-butadiene are above the 95th percentile of annual average, national, concentrations. However, the samples taken in Sacramento on forecasted high $PM_{2.5}$ days are likely biased higher, relative to a standard 1-in-6 day annual sampling strategy that would have a more even representation of high and low concentrations days. Concentrations for pollutants such as carbon tetrachloride, acetonitrile, and acrolein, were closer to annual average concentrations seen at other U.S. monitoring sites.[7] For all parameters with cancer benchmarks, the average concentrations were above the 1-in-a-million cancer risk level. However, the ambient data are not annual averages. Ethylbenzene, carbon tetrachloride, benzene, and 1,3-butadiene concentrations in Sacramento were all higher than these risk levels, similar to other urban areas (McCarthy et al., 2006). For chronic REL, only acrolein was above the level of concern; acrolein is a respiratory irritant.

[7] Carbon tetrachloride is the same everywhere in the U.S. since it is no longer emitted and has a long atmospheric lifetime. Acetonitrile and acrolein concentrations were typically near or below detection.

Table 12. MDL and site concentrations (ppb) for each HAP, and p-value of significance between all EJ and non-EJ sites. **Bold** indicates significant differences at the 95% confidence level used by the Mann-Whitney U-test. Sites are ordered by non-EJ/EJ pair.

Analyte	MDL	64th St. (Non-EJ)	Tristan (EJ)	T. St (Non-EJ)	Socorro Way (EJ)	Del Paso Manor (Non-EJ)	Darwin (EJ)	All Non-EJ	All EJ	p-Value (Between All Non-EJ and All EJ Sites)
1,3-Butadiene	0.026	0.17	0.16	0.17	0.22	0.15	0.22	0.16	0.18	0.12
2,2,4-Trimethylpentane	0.01	0.30	0.37	0.29	0.45	0.34	0.47	0.31	0.37	**0.02**
Acetonitrile	0.051	0.13	0.12	0.15	0.16	0.15	0.14	0.14	0.14	0.33
Acetylene	0.029	3.71	3.16	2.90	2.90	2.15	3.08	2.92	2.99	0.21
Acrolein	0.12	0.23	0.29	0.32	0.26	0.23	0.34	0.26	0.27	**<0.01**
Benzene	0.021	0.56	0.59	0.60	0.78	0.58	0.80	0.58	0.65	**0.05**
Carbon Tetrachloride	0.016	0.08	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.07
Ethylbenzene	0.019	0.18	0.19	0.21	0.24	0.15	0.26	0.18	0.20	**0.02**
m,p-Xylene	0.04	0.52	0.56	0.60	0.81	0.48	0.90	0.53	0.64	**<0.01**
Toluene	0.017	0.97	1.29	1.15	1.70	0.97	1.65	1.03	1.34	**<0.01**

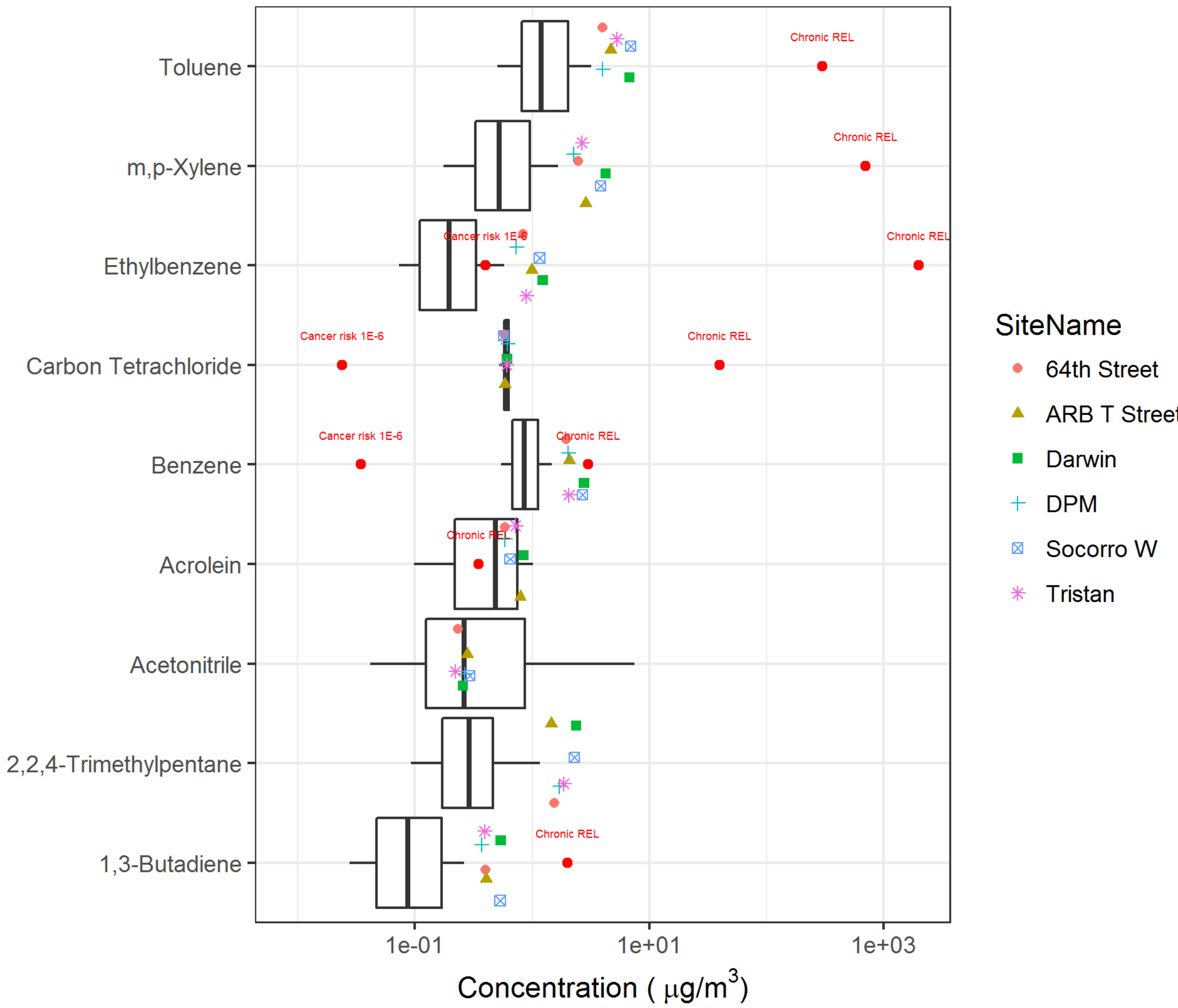


Figure 7. Average HAP concentrations (µg/m^3) by Sacramento site (symbols) for samples collected from December 2016–January 2017, California cancer risk and non-cancer chronic reference exposure level (REL), and box plots of 10th, 25th, median, 75th, and 90th percentile of average winter (December-February) concentrations (µg/m^3) across all U.S. sites for 2014-2016.[8] DPM stands for Del Paso Manor.

3.1.3 HAP Day/Night Variations

The two likely sources of HAPs in this study—mobile sources and wood burning—peak at different times; mobile source emissions peak in the morning during the commute hours with a secondary peak in the evening, while wood burning emissions peak in the evening. Thus, having samples in

[8] A box-whisker plot shows the entire distribution of concentrations for a site. The box shows the range between the 25th and 75th percentiles, the vertical line shows the median, and whiskers show data beyond the interquartile range.

both daytime and nighttime pairs allows for a comparison of whether HAPs are predominantly from mobile sources or wood burning. For example, if HAP concentrations are higher in the daytime, mobile sources are a more important source of those HAPs than residential wood burning, which predominantly occurs at night. HAP samples were typically collected during four sequential 12-hour daytime and nighttime periods; e.g., samples were taken starting at 18:00 to 06:00 PST, then at 06:00 PST and 18:00 PST the following day, and at 06:00 PST the day after that.

First, the day/night trends of carbon tetrachloride (CCl_4), a very long-lived HAP that is no longer emitted in the U.S., were examined. It was phased out as part of the Montreal Protocol to ban chlorofluorocarbons (CFCs) to repair the ozone hole. Because it has a very long residence time in the atmosphere, it is very homogeneous, and concentrations should be approximately 0.085 ppb everywhere in the U.S. The spatial and time-of-day variations should be minimal, and any deviations would indicate sampling and analytical imprecision. As seen in Figure 8, the results show no systematic bias across sites or time-of-day. This indicates high-quality sampling and analysis results.

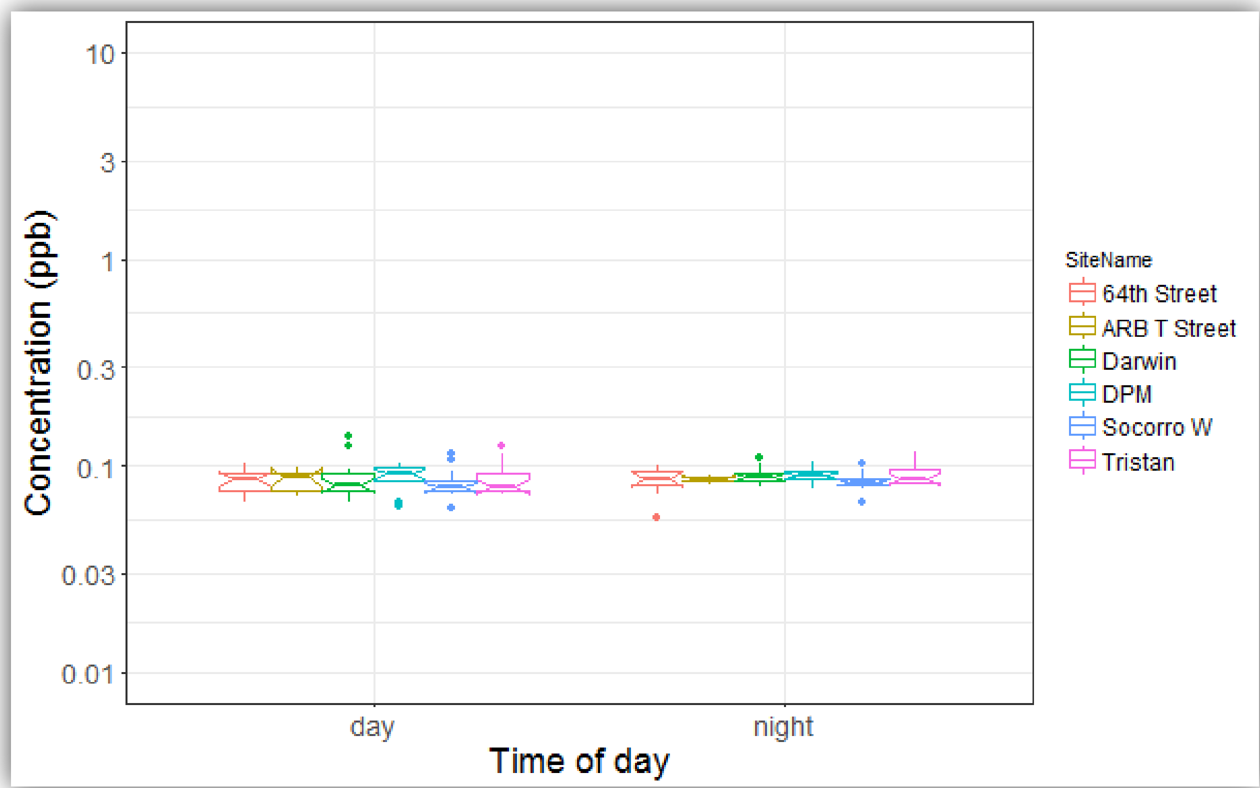


Figure 8. Box plot of daytime and nighttime carbon tetrachloride concentrations (ppb) by site. The box plots show the median concentration as the lines in the middle of the boxes, the interquartile range (25th-75th percentile, IQR) as the edges of the boxes, the 95% confidence interval as the notches, and 1.5 x IQR as the error bars. Outliers beyond 1.5 x IQR are shown as points. DPM stands for Del Paso Manor.

In contrast to carbon tetrachloride, most of the HAPs showed large differences between daytime and nighttime concentrations. Statistical tests of daytime/nighttime differences are summarized in Table 13. Multiple sites recorded higher daytime concentrations for all species except carbon tetrachloride. Daytime concentrations of most HAPs were consistently higher at the Darwin, Del Paso Manor (shown as DPM in some tables and figures), Socorro, and Tristan sites; Figure 9 shows a daytime/nighttime notched box plot for benzene as an example. Higher concentrations in the daytime indicates that the dominant sources of HAPs are more likely mobile source emissions than wood smoke emissions.

Table 13. Summary of Kruskal-Wallis estimates of distribution differences between daytime and nighttime concentrations of HAPs. All values in **bold** are statistically significantly higher daytime concentrations at greater than 95% confidence level. Values in italics are daytime concentrations at 90% confidence levels.

Pollutant	64th Street	ARB T Street	Darwin	DPM	Socorro	Tristan
1,3-Butadiene	*0.056*	0.734	**0.023**	**0.001**	**0.002**	**0.015**
2,2,4-Trimethylpentane	*0.074*	0.395	**0.003**	**0.002**	**0.003**	**0.028**
Acetonitrile	0.854	0.308	**0.001**	**0.000**	**0.009**	0.225
Acetylene	**0.016**	0.734	**0.003**	**0.001**	**0.002**	0.157
Acrolein	0.442	**0.041**	0.954	**0.002**	0.453	0.603
Benzene	*0.074*	0.734	**0.002**	**0.001**	**0.006**	**0.028**
Carbon Tetrachloride	0.579	0.865	0.118	0.927	0.248	*0.073*
Ethylbenzene	*0.090*	0.734	**0.003**	**0.005**	**0.006**	**0.038**
m,p-Xylene	*0.097*	0.610	**0.007**	**0.005**	**0.007**	**0.021**
Toluene	*0.074*	0.610	**0.002**	**0.004**	**0.006**	**0.043**

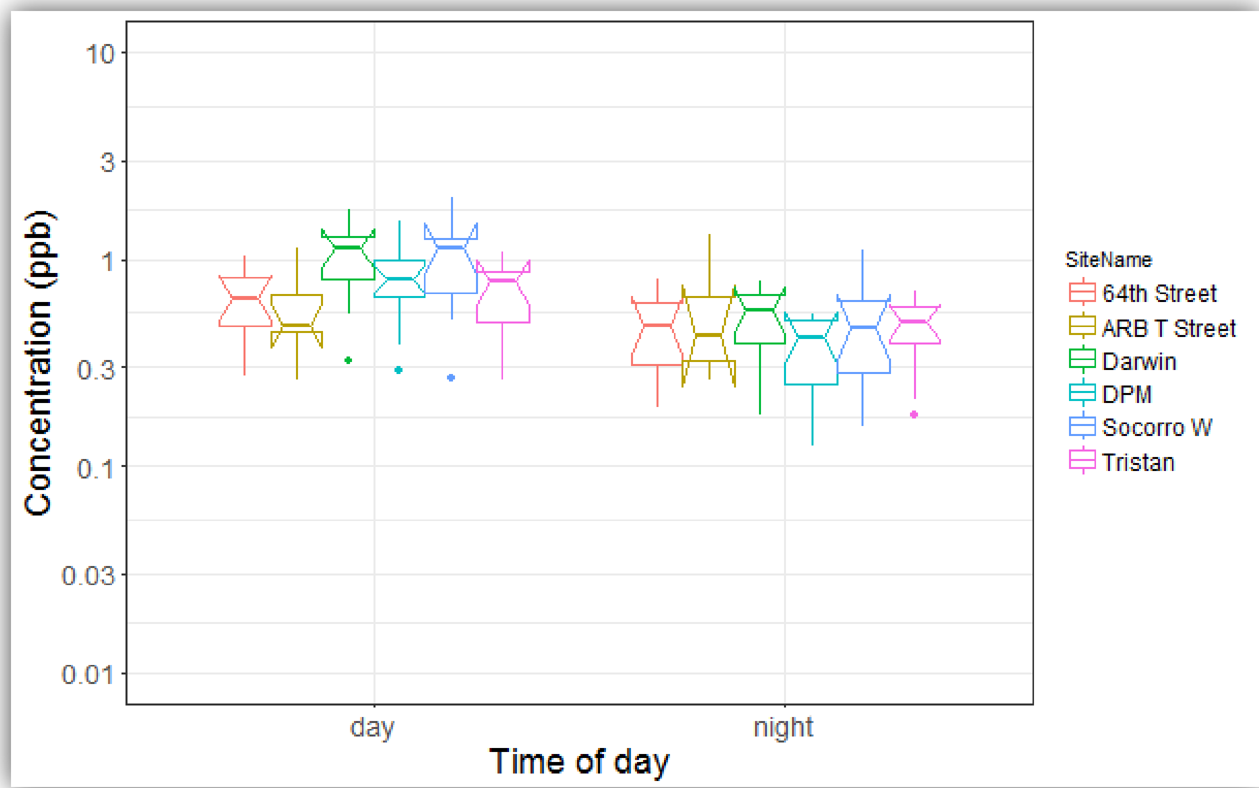


Figure 9. Box plot of daytime and nighttime benzene concentrations (ppb) by site. Box plots show the median concentration as the lines in the middle of the boxes, the interquartile range (25^{th} -75^{th} percentile; IQR) as the edges of the boxes, the 95% confidence interval as the notches, and 1.5 x IQR as the error bars. Outliers beyond 1.5 x IQR are shown as points. DPM stands for Del Paso Manor.

3.2 Filter Sample Results

3.2.1 Collocated Filter Results

Filters were collected at the Del Paso Manor, T Street, and Tristan sites, and a total of five collocated filters were collected at Tristan to evaluate precision for levoglucosan, OC, and EC. Results of collocated measurements at Tristan are shown in Figure 10. The high correlation (R^2) value for levoglucosan indicates very high precision (R^2=0.99). EC also had very high precision (R^2=0.90), and OC had modestly high precision (R^2=0.74). The high precision for levoglucosan suggests there is very high confidence in the measurement results.

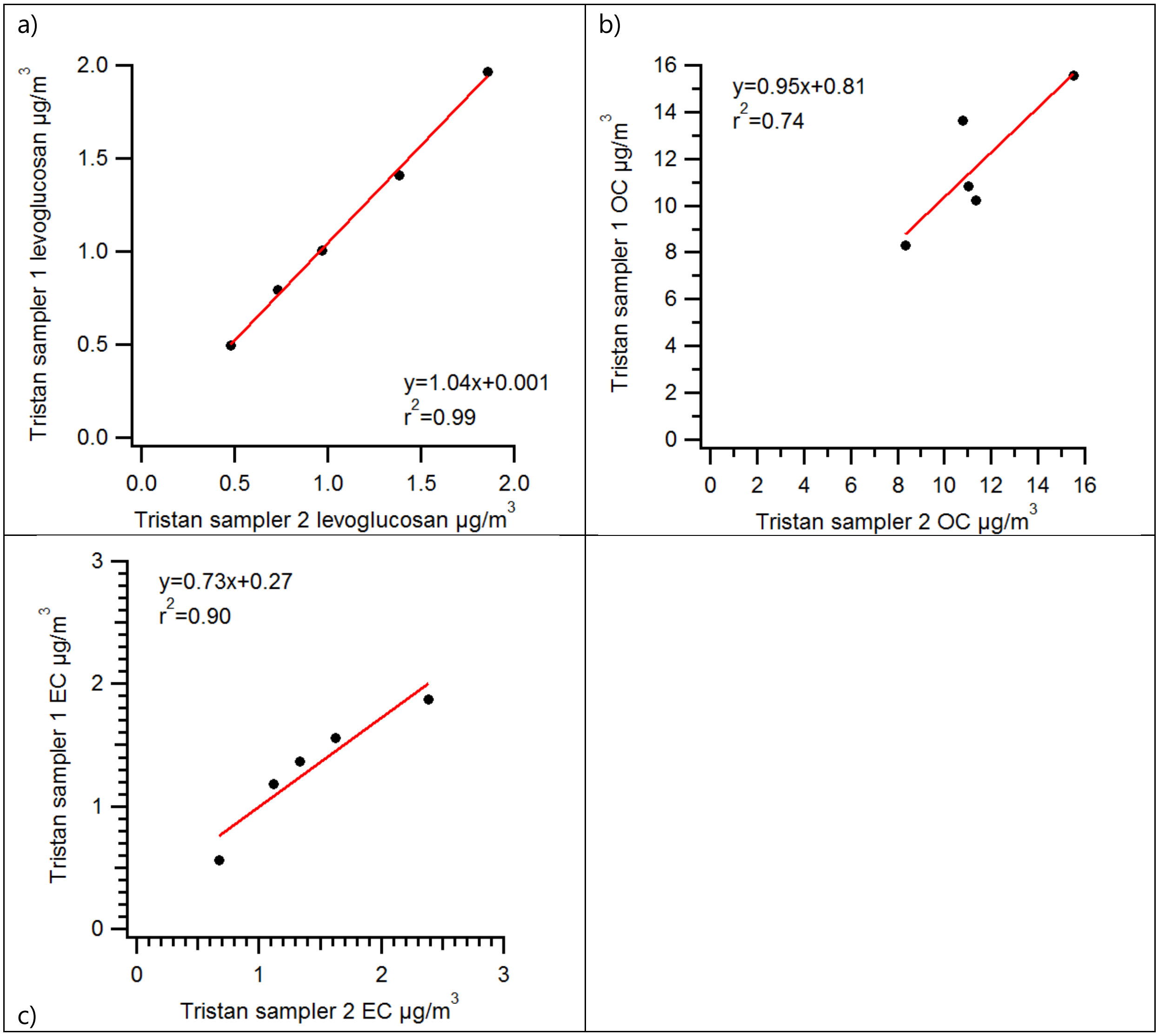


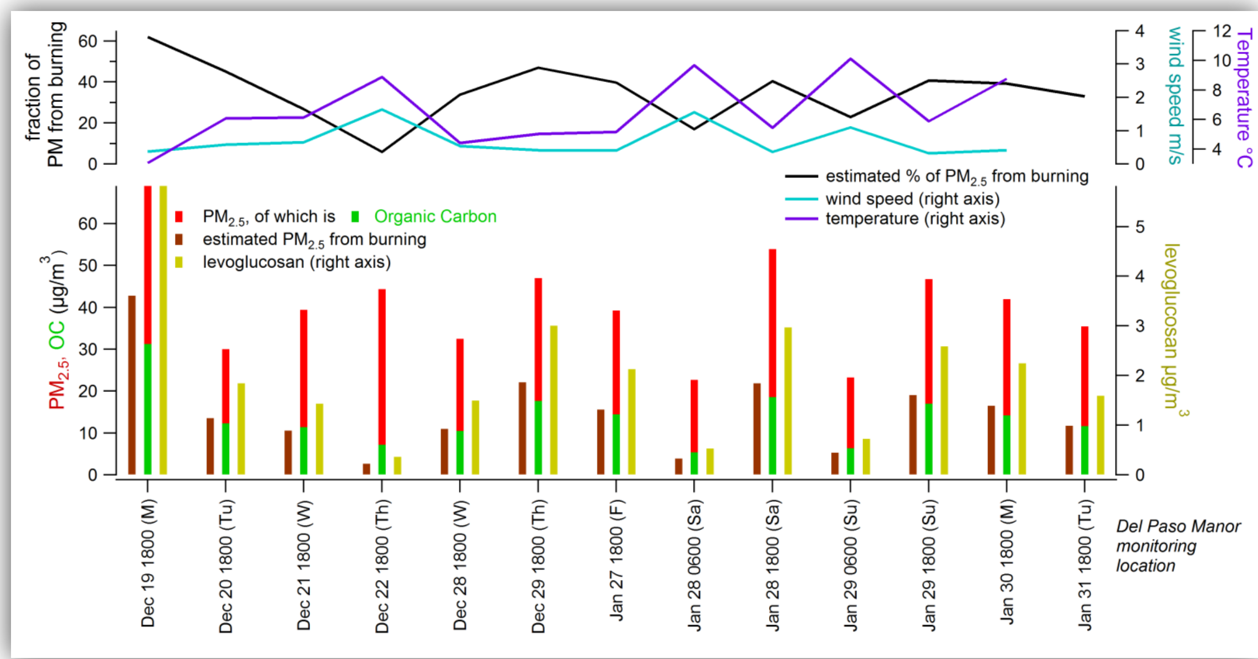
Figure 10. Collocated filter results at the Tristan site for (a) levoglucosan, (b) OC, and (c) EC.

3.2.2 Levoglucosan Concentrations and Estimated Wood Burning PM

Levoglucosan is a unique tracer for wood burning emissions, collected via filters, and is used here to estimate wood burning $PM_{2.5}$. Filter results are summarized by site in Table 14 and are shown in Figures 11 through 13. At each site, wood burning PM was calculated, as described in Section 2. Figure 14 shows the amount of burning PM at each site by sample. At the Del Paso Manor and T Street sites, the fraction of $PM_{2.5}$ from wood burning was also calculated (shown in Figure 15), using hourly BAM measurements of $PM_{2.5}$. Overall, levoglucosan and wood burning PM concentrations were highest at the Del Paso Manor site, and the T Street and Tristan sites were similar to each other. At the Del Paso Manor site, wood burning accounted for 39% of the PM concentrations during the filter sampling periods. At the T Street site, wood burning accounted for 29% of the PM concentrations. At the Tristan site, the concentration of wood burning PM was similar to that at the T Street site (6.8 µg/m^3 at the Tristan site, and 6.3 µg/m^3 at the T Street site), and about half of the concentration at the Del Paso Manor (13.5 µg/m^3) site. These results indicate that wood burning emissions are highest around the Del Paso Manor site, but are still responsible for a significant amount of the PM at T Street and Tristan. OC and EC concentrations were higher at Del Paso Manor than at other study sites, similar to results for levoglucosan, and are from wood burning as well as other sources.

Table 14. Summary of filter results (µg/m^3) by site.

Statistic	Del Paso Manor	T Street	Tristan
N 12-hr samples (N night)	13 (11)	13 (11)	10 (8)
Median OC	12.3	11.0	10.5
Median EC	1.6	1.4	1.3
Median BAM $PM_{2.5}$	39	24	n/a
Median levoglucosan	1.84	0.86	0.93
Median wood burning PM	13.5	6.3	6.8
% PM from wood burning	39%	29%	n/a
OC/Wood Burning PM Ratio	0.91	1.74	1.54



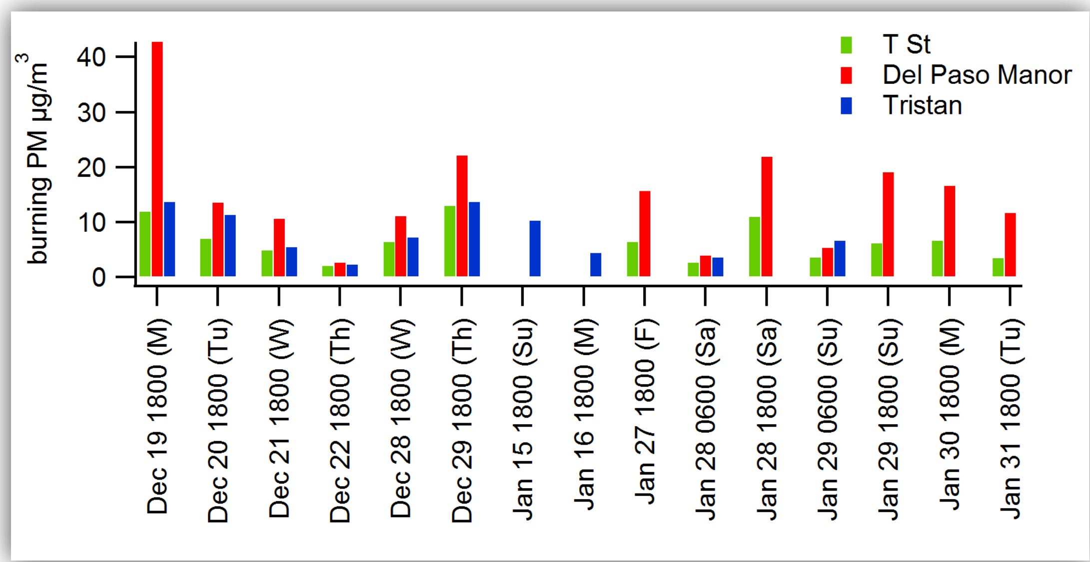


Figure 11. Concentrations of organic carbon and $PM_{2.5}$, and estimated $PM_{2.5}$ from burning (left axis, µg/m^3), levoglucosan (right axis, µg/m^3), estimated fraction of PM from burning (top left axis), wind speed (top right axis, m/s), and average temperature (top right axis, degrees Celsius) measured at the Del Paso Manor site by sample date.

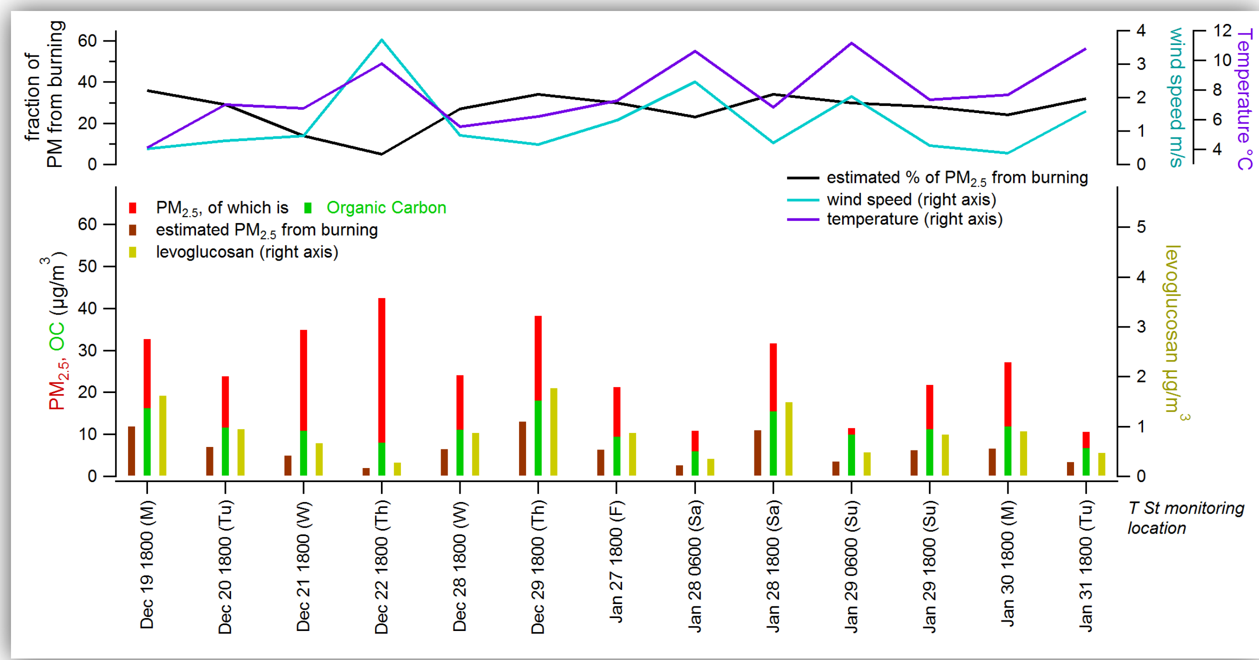


Figure 12. Concentrations of organic carbon and $PM_{2.5}$, and estimated $PM_{2.5}$ from burning (left axis, µg/m^3), levoglucosan (right axis, µg/m^3), estimated fraction of PM from burning (top left axis), wind speed (top right axis, m/s), and average temperature (top right axis, degrees Celsius) measured at the T Street site by sample date.

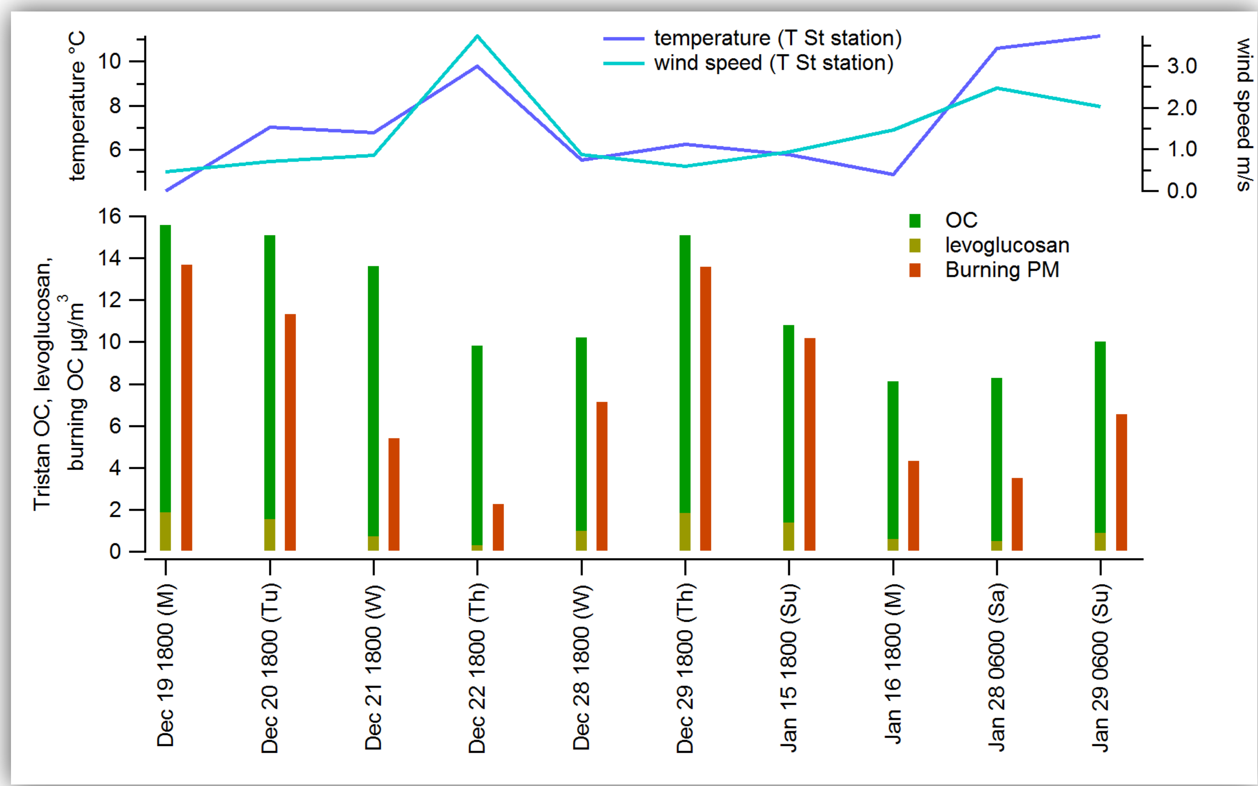


Figure 13. Levoglucosan, organic carbon, and estimated $PM_{2.5}$ from burning (left axis, µg/m^3), wind speed (top right axis, m/s), and average temperature (top left axis, degrees Celsius) measured at the Tristan site by sample date. Meteorological data taken from the T Street site.

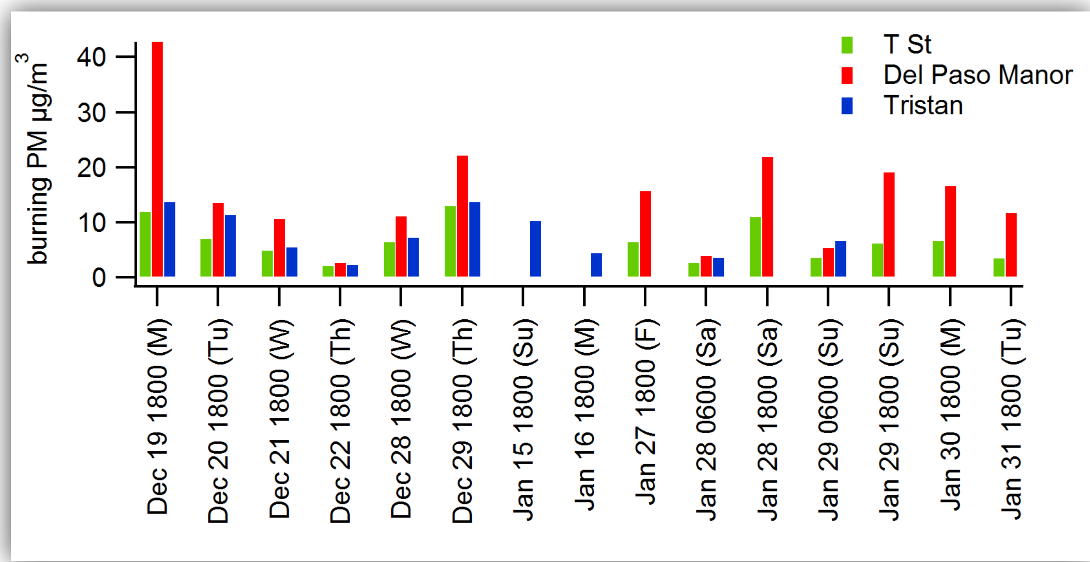


Figure 14. Burning PM (µg/m^3) by site and sample date.

3.2.3 Burning PM by Daytime/Nighttime

Nighttime concentrations were compared to two daytime samples collected at each site. The daytime/nighttime analysis for HAPs indicated that residential wood burning predominantly occurs at night; therefore, levoglucosan found during the daytime is likely carried over from the prior night. On January 28 and 29, 2017, two daytime samples were collected at 06:00-18:00 PST at each site to provide a rough comparison of daytime concentrations to nighttime concentrations. Figure 15 shows the average of burning PM concentrations for the two daytime samples compared to two nighttime samples collected on January 27, 28, and 29 at the Del Paso Manor and T Street sites, and on January 15 and 16 at the Tristan site. Del Paso Manor and T Street both had sequential samplers, enabling both nighttime and daytime filters to be collected, while Tristan had mini-vol samplers that collect only one filter at a time. Daytime samples were not collected at Tristan on January 27-29 because nighttime samples were collected. Nighttime concentrations of burning PM were four times higher than daytime concentrations at Del Paso Manor, roughly twice as high as daytime concentrations at the T Street sites, and roughly 50% higher than daytime concentrations at Tristan. Daytime concentrations of burning PM were similar at all three sites. These results suggest that wood burning PM is well distributed across these three sites during the daytime, and is elevated around Del Paso Manor during the nighttime.

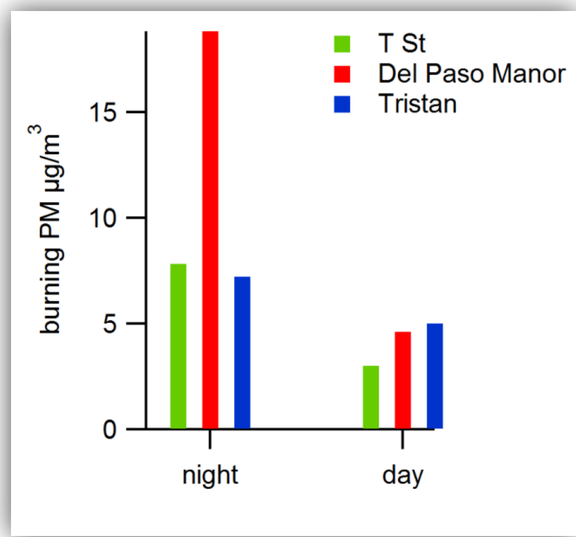


Figure 15. Average burning $PM_{2.5}$ concentrations ($\mu g/m^3$) during daytime samples (January 28 and 29, 2017, at the Del Paso Manor, T Street, and Tristan sites) and nighttime samples (January 27 through 29, 2017, at the Del Paso Manor and T Street sites, and January 15 through 16, 2017, at the Tristan site).

3.3 Black Carbon

3.3.1 Community Comparison of BC

BC concentrations were compared among community sites to assess whether EJ or non-EJ sites had higher concentrations. BC concentrations by site are shown in Figure 16, and are separated out by BC_{ff} and BC_{wb} in Figures 17 and 18. Overall, BC and BC_{wb} concentrations are significantly higher at the Del Paso Manor site compared to the other sites, while BC_{ff} is generally similar across all sites (as shown in Tables 15 through 17). Based on Mann-Whitney U-tests, BC and BC_{wb} concentrations differed between the EJ and non-EJ sites at the 95% confidence level, as EJ communities showed slightly lower concentrations of both pollutants than non-EJ communities. BC_{ff} concentrations were not significantly different between the two community types. Significant site-to-site variations were observed, where BC concentrations at the EJ Socorro site were significantly higher than the nearby non-EJ T Street site, while concentrations at the 64th Street and Del Paso Manor non-EJ sites were significantly higher than the Tristan and Darwin EJ sites.

BC_{ff} concentrations were not significantly different among all of the community sites, except for the Socorro site, indicating relatively homogeneous BC_{ff} impacts across all sites. BC_{ff} concentrations measured at the Socorro site were significantly higher than at the other sites, except for the 64th Street site; this may indicate the presence of a fossil fuel emission source near the Socorro site.

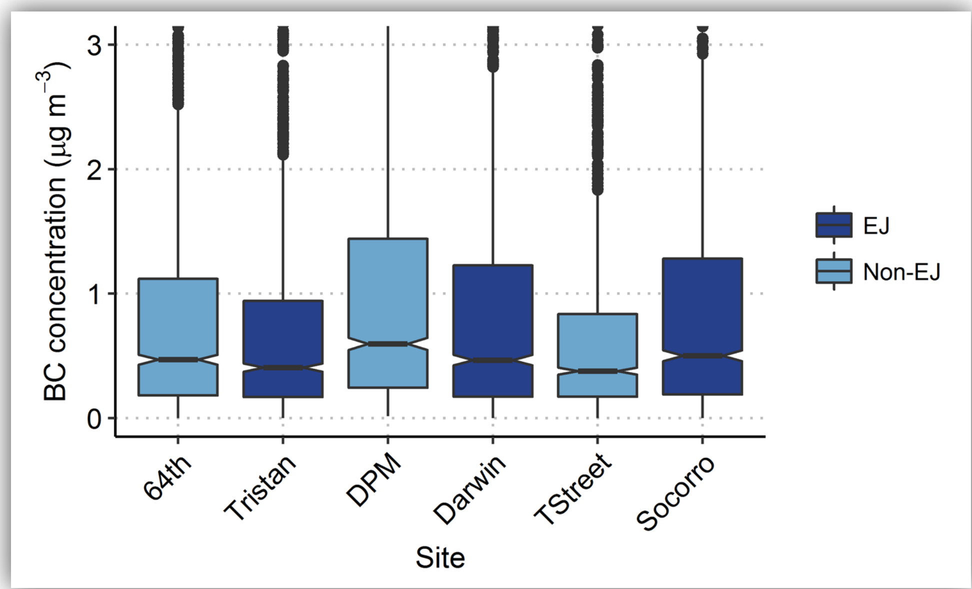


Figure 16. Notched box plot of BC concentrations by site from December 2016 through January 2017. Data values above 3.1 µg/m^3 are not shown. DPM is Del Paso Manor.

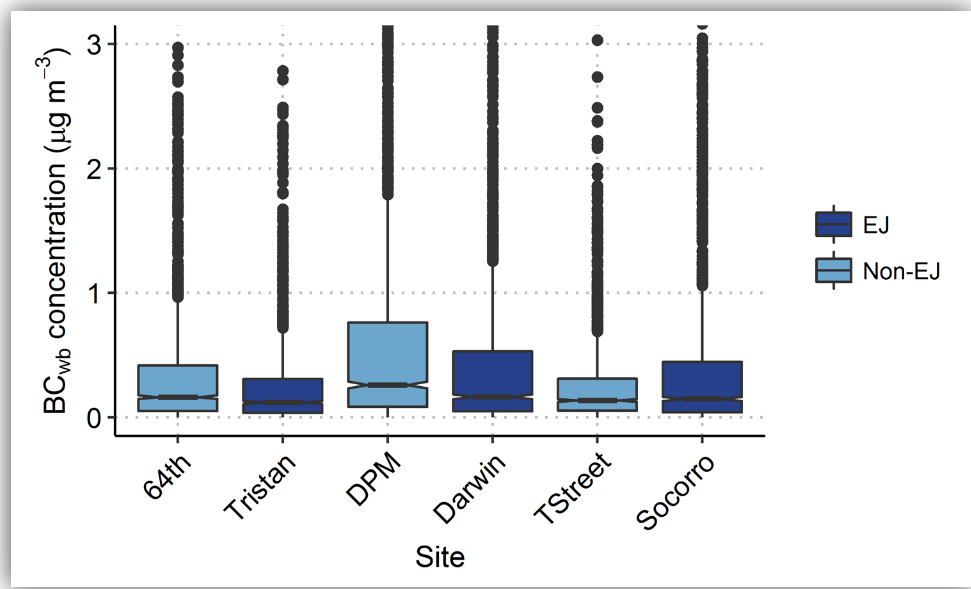


Figure 17. Notched box plot of BC_{wb} concentrations by site from December 2016 through January 2017. Data values above 3.1 µg/m^3 are not shown. DPM is Del Paso Manor.

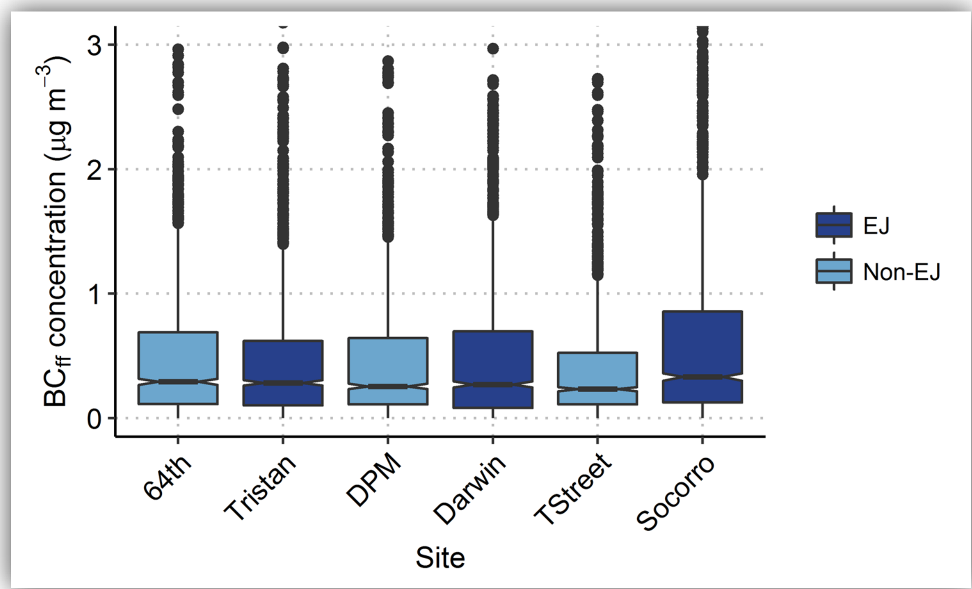


Figure 18. Notched box plot of BC_{ff} concentrations by site from December 2016 through January 2017. Data values above 3.1 µg/m^3 are not shown. DPM is Del Paso Manor.

Table 15. Significance of posthoc Nemenyi-tests for pairwise multiple comparisons for BC between each community. Values below 0.05 (**bold**) indicate a statistically significant difference between the pair of communities. The median, mean, and standard deviation (SD) of the BC values measured at each community is also indicated.

BC	Median (Mean/SD)	64th Street	Tristan	Del Paso Manor	Darwin	T Street
		0.45 (0.87/1.07)	0.40 (0.75/0.92)	0.57 (1.22/1.67)	0.45 (1.02/1.42)	0.38 (0.69/0.83)
Tristan	0.40 (0.75/0.92)	0.223	-	-	-	-
Del Paso Manor	0.57 (1.22/1.67)	**0.000**	**0.000**	-	-	-
Darwin	0.45 (1.02/1.42)	0.994	0.534	**0.000**	-	-
T Street	0.38 (0.69/0.83)	**0.069**	0.997	**0.000**	0.241	-
Socorro	0.47 (1.17/1.71)	0.922	**0.011**	**0.007**	0.615	**0.001**

Table 16. Significance of posthoc Nemenyi-tests for pairwise multiple comparisons between each community for BC_{wb}. Values below 0.05 (**bold**) indicate a statistically significant difference between the pair of communities. The median, mean, and SD of the BC_{wb} concentration measured at each community is also indicated.

BC_{wb}	Median (Mean/SD)	64th	Tristan	Del Paso Manor	Darwin	T Street
		0.15 (0.40/0.70)	0.12 (0.27/0.43)	0.26 (0.77/1.34)	0.16 (0.51/0.90)	0.14 (0.27/0.39)
Tristan	0.12 (0.27/0.43)	**0.001**	-	-	-	-
Del Paso Manor	0.26 (0.77/1.34)	**0.000**	**0.000**	-	-	-
Darwin	0.16 (0.51/0.90)	0.963	**0.000**	**0.000**	-	-
T Street	0.14 (0.27/0.39)	0.529	0.313	**0.000**	**0.096**	-
Socorro	0.14 (0.44/0.75)	0.794	0.103	**0.000**	0.246	0.998

Table 17. Significance of posthoc Nemenyi-tests for pairwise multiple comparisons between each community for BC_{ff}. Values below 0.05 (**bold**) indicate a statistically significant difference between the pair of communities. The median, mean, and SD of the BC_{ff} concentrations measured at each community is also indicated.

BC_{ff}	Median (Mean/SD)	64th	Tristan	Del Paso Manor	Darwin	T Street
		0.28 (0.47/0.28)	0.28 (0.48/0.28)	0.25 (0.45/0.25)	0.26 (0.50/0.26)	0.23 (0.41/0.23)
Tristan	0.28 (0.48/0.28)	0.833	-	-	-	-
Del Paso Manor	0.25 (0.45/0.25)	0.915	1.000	-	-	-
Darwin	0.26 (0.50/0.26)	0.341	0.979	0.927	-	-
T Street	0.23 (0.41/0.23)	0.139	0.846	0.706	0.997	-
Socorro	0.32 (0.73/0.32)	0.123	**0.002**	**0.003**	**0.000**	**0.000**

3.3.2 Temporal Variation of BC

The diurnal and day-of-week variations in BC, BC_{wb}, and BC_{ff} were examined to investigate the temporal patterns of concentrations of these species. Fossil fuel sources are expected be highest during the morning and evening commutes, and wood burning is expected to be highest during the evening. Day-of-week patterns may also exist, as there is typically less driving on Sundays compared to weekdays (Valin et al., 2014; Yarwood et al., 2008; Blanchard et al., 2008; Brown et al., 2014), and there may be less residential biomass burning on weekdays compared to weekends.

Figures 19 through 21 show the median and 95% confidence intervals around the median for diurnal and day-of-week concentrations by site for BC, BC_{wb}, and BC_{ff}. In Sacramento, the T Street site has a typical urban diurnal pattern with elevated morning BC, while other sites have a nighttime peak in BC that is higher than the BC morning peak. For all sites, BC_{wb} is much higher at night than during the morning or daytime consistent with expected wood burning patterns. There is also a large variation in nighttime BC and BC_{wb} concentrations, as seen by the large confidence interval surrounding the median line in the plots. Overall, results suggest that all sites but T Street have a strong impact from wood burning in the evening, while T Street concentrations show only a modest impact. BC_{ff} has a typical diurnal pattern of morning and evening peaks consistent with morning and evening rush hour traffic. The day-of-week patterns for BC, BC_{wb}, and BC_{ff} are unexpected, with a large drop in all species concentrations between Wednesday and Thursday. Since only eight weeks of data were collected, variations are likely due to stochastic events such as rainfall (which would decrease concentrations), rather than consistent robust differences in emissions on Wednesday and Thursday compared to other days.

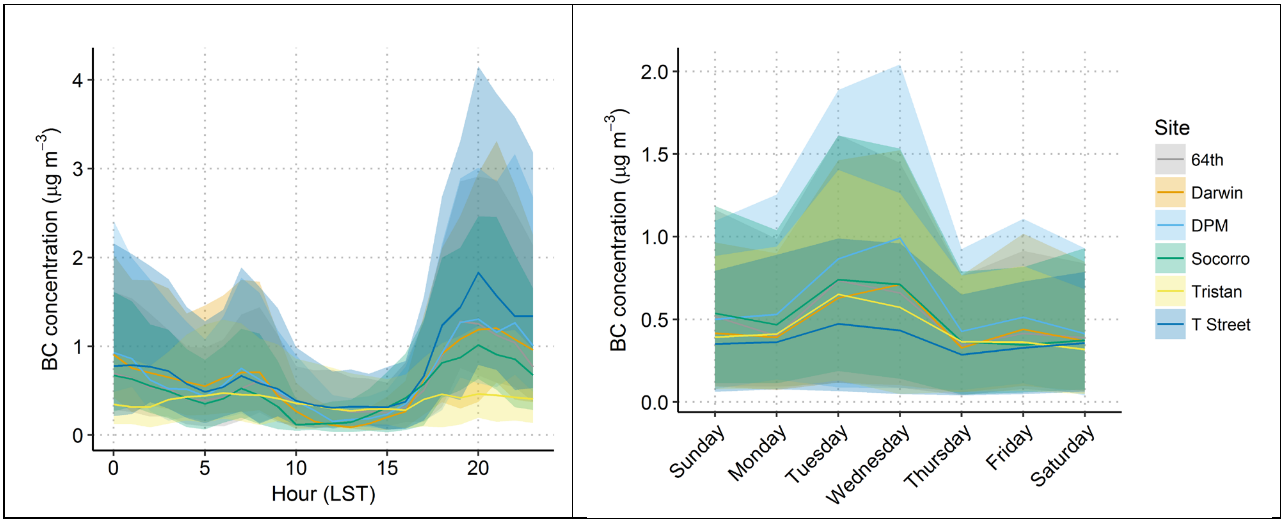


Figure 19. Diurnal (left) and day-of-week (right) plots for BC by site; the median is shown as a line, and the shading indicates the 95th confidence interval around the median. The 95th confidence interval is calculated based on the rank ordered data values obtained from the binomial quantile function at probabilities 0.025 and 0.975. DPM is Del Paso Manor.

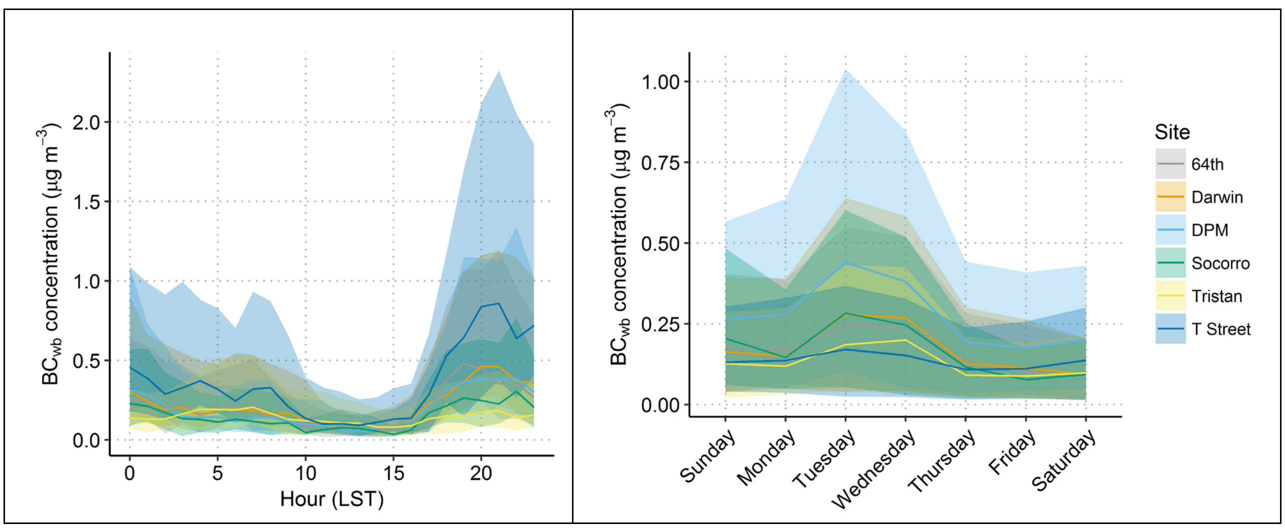


Figure 20. Diurnal (left) and day-of-week (right) plots for BC_{wb} by site; the median is shown as a line, and the shading indicates the 95th confidence interval around the median. The 95th confidence interval is calculated based on the rank ordered data values obtained from the binomial quantile function at probabilities 0.025 and 0.975. DPM is Del Paso Manor.

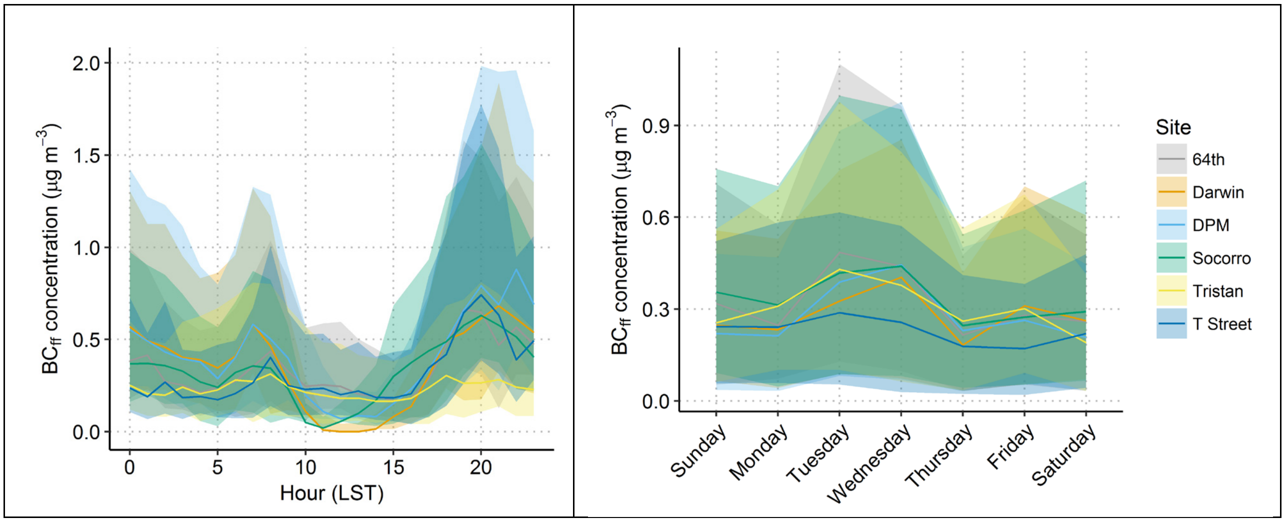


Figure 21. Diurnal (left) and day-of-week (right) plots for BC_{ff} by site; the median is shown as a line, and the shading indicates the 95th confidence interval around the median. The 95th confidence interval is calculated based on the rank ordered data values obtained from the binomial quantile function at probabilities 0.025 and 0.975. DPM is Del Paso Manor.

BC concentrations on holiday nights (December 24, December 25, and December 31, 2016, and January 1, 2017) were compared to concentrations on non-holiday evenings to understand whether holidays were aberrant compared to non-holidays. Winds were light (less than 5 mph on average) and minimal (0.01 inches) to no precipitation was observed on these dates. Figure 22 shows a time series of BC concentrations for December 22, 2016, through January 2, 2017, at all sites. There was a distinct elevation in BC concentration on Christmas Eve at all sites, except for the T Street site, where only a very limited impact was observed. For the 64th Street, Darwin, and Socorro sites, the highest BC values recorded for the entire 2-month study period occurred on Christmas Eve. The combination of light winds, no precipitation, and typically higher wood burning activity due to the holiday likely led to the high BC values on December 24. A moderate elevation in BC was also seen at all sites on New Year’s Eve. Concentrations were only modestly higher on Christmas Day compared to other days in late December through early January, except at the T Street and Tristan sites.

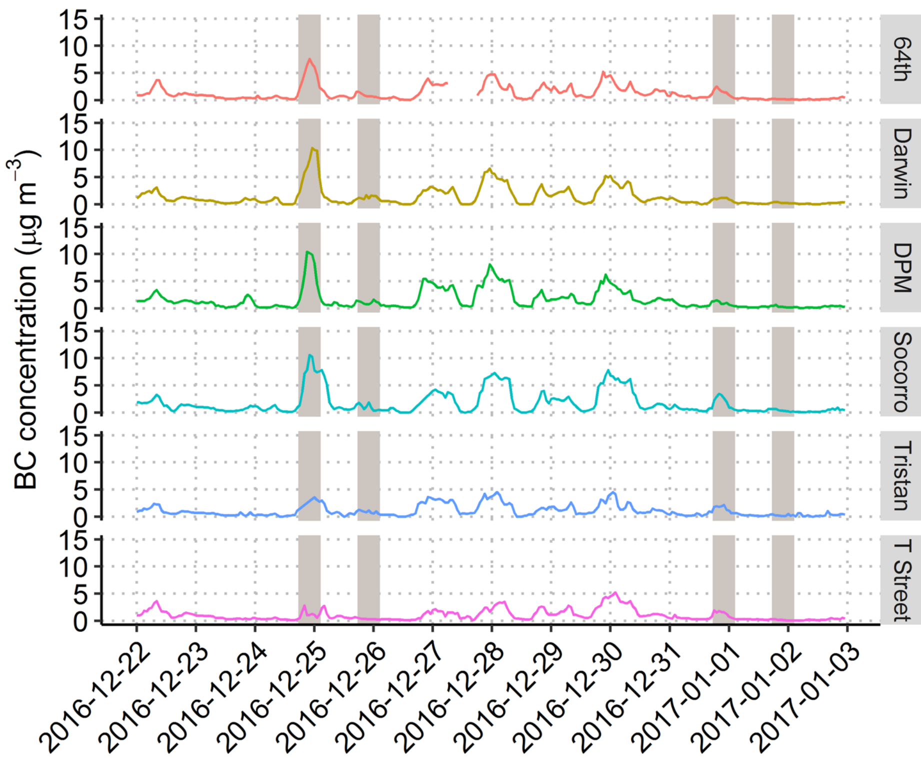


Figure 22. Time series of BC for December 22, 2016, through January 2, 2017. Evening hours of holidays (Christmas Eve, Christmas Day, New Year's Eve, and New Year's Day) are indicated with vertical gray bars. DPM is Del Paso Manor.

3.3.3 BC by Check Before You Burn Day

The differences in the concentration of BC, BC_{wb}, and BC_{ff} on Check Before You Burn (CBYB)[9] days were compared to other days. There are four levels to CBYB: legal to burn, burning discouraged, no burning unless exempt (Stage 1), and all burning prohibited (Stage 2). Stage 1 and Stage 2 days are those that are forecast to have high $PM_{2.5}$ concentrations (between 32-35 µg/m^3 for Stage 1, and above 35 µg/m^3 for Stage 2). During the study, there were 18 Stage 2 days, 10 Stage 1 days, 9 "burning discouraged" days, and 25 "legal to burn" days. At all sites, Stage 1 and 2 days had higher concentrations of BC, BC_{wb}, and BC_{ff} compared with "legal to burn" days (Figure 23). This is expected, since Stage 1 and 2 days are issued because the meteorological conditions are conducive to higher $PM_{2.5}$ concentrations; these results cannot be used to assess the effectiveness of the Stage 1 or 2 level alerts, since it is unknown what concentrations would have been like without these alerts.

[9] http://www.airquality.org/residents/fireplaces-wood-stoves/check-before-you-burn .

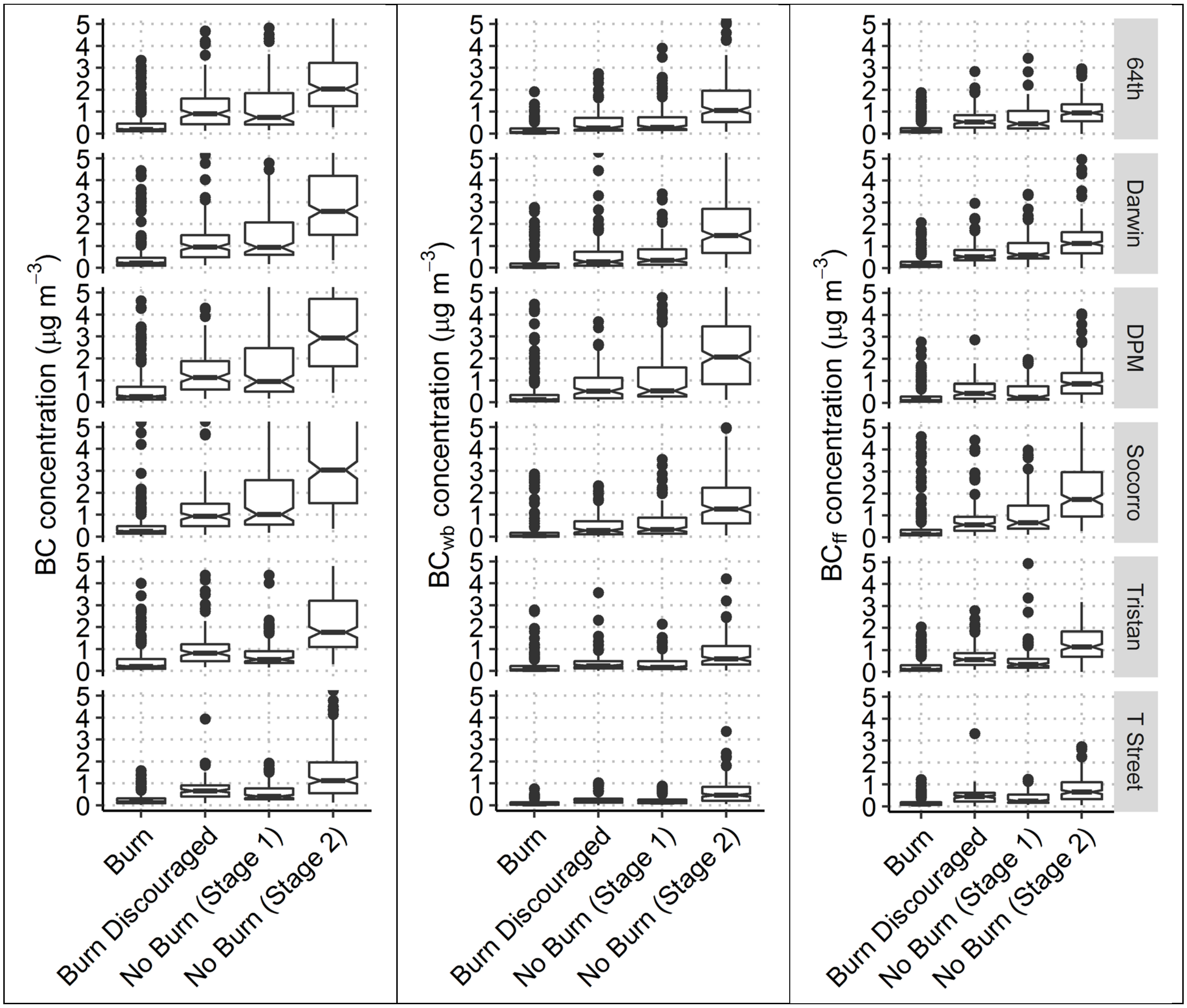
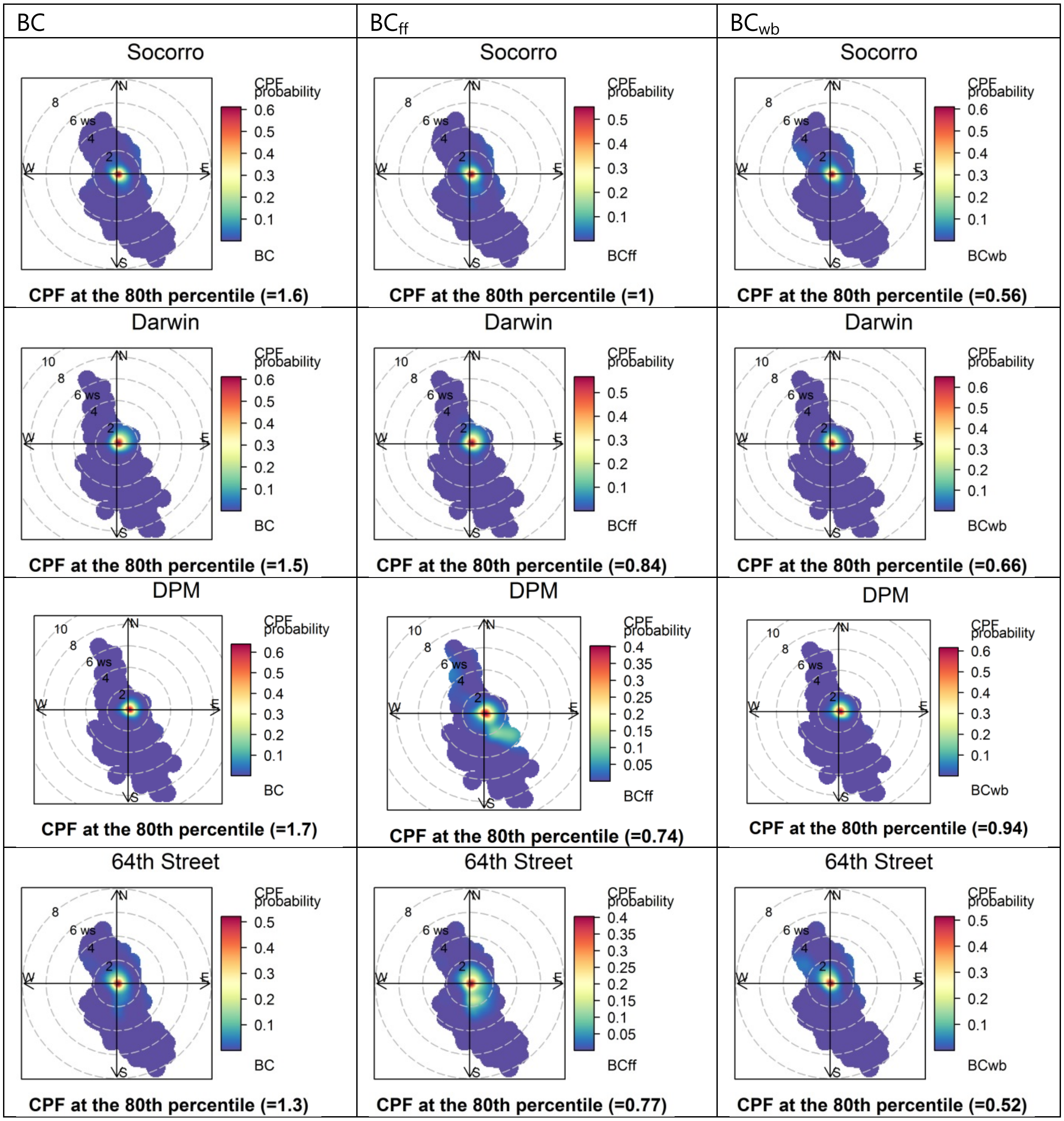


Figure 23. Box-and-whisker plots of BC (left), BC_{wb} (center), and BC_{ff} (right) on days when burning is allowed, when burning is discouraged, and when burning restrictions are enforced (at Stage 1 and Stage 2 levels) for each site with BC data. Data values greater than 5 µg/m^3 are not displayed so that medians can be more easily visualized. DPM is Del Paso Manor.

3.3.4 Wind Direction Analysis

Hourly BC, BC_{wb}, and BC_{ff} measurements were combined with meteorological data to try to identify the likely source of these pollutants. CBPF was used to identify wind speeds and directions associated with the highest quintile of concentrations. For all sites in this study, the highest quintile of concentrations of BC, BC_{ff}, and BC_{wb} occurred at very low wind speeds (Figure 24) associated with stable and stagnant conditions. At the T Street site, there were also high concentrations under high-speed winds from the northwest. However, closer examination revealed that this was caused by just 3 hours in early December, during which BC_{wb} concentrations were high and wind speeds were also high. It is unlikely that this result indicates a true source of BC_{wb}. For BC_{ff}, the plots suggest that minor impacts from fossil fuel sources exist south-southeast of the 64th Street, Del Paso Manor, and T Street sites.



(Figure continued on following page.)

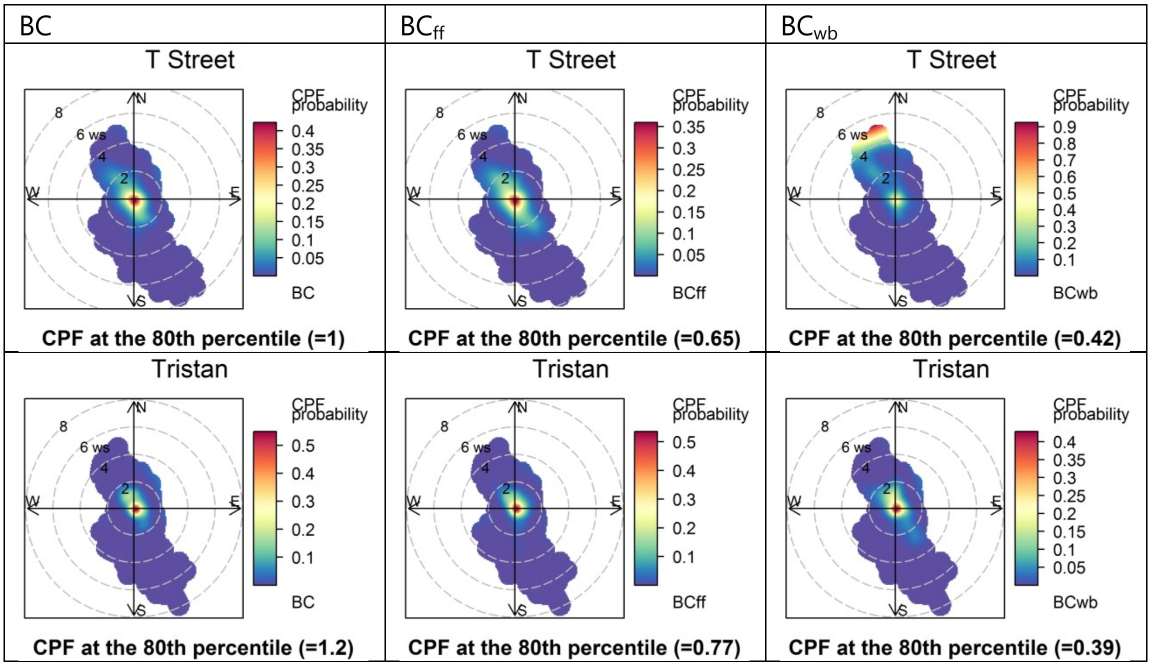


Figure 24. CBPF plots for the highest quintile of BC (left column), BC_{ff} (middle column), and BC_{wb} (right column) concentrations, labeled by site. Color indicates the probability that the pollutant concentrations measured at a given wind speed and direction fell within the top quintile of all pollutant concentrations measured at that site (the CPF probability). Wind speeds are denoted in the concentric circles (m/s). Red and yellow indicate that concentrations within the top quintile are more likely.

3.4 Sensor PM Results

Results in this and subsequent sections use corrected sensor data, as described in Section 2 and Appendix B.

3.4.1 Sensor Precision and Correction

Sensor precision and bias were assessed using collocated measurement periods before, during, and after the study. The sensors demonstrated high precision throughout all periods, allowing the development of a normalization correction, as shown in Appendix B. The coefficient of determination (R^2 value) of each individual AirBeam compared to the combined mean of all 19 AirBeams provides a representation of sensor precision. The AirBeams demonstrate very high precision during these collocation periods, with R^2 values ranging from 0.98 to 0.999. This means that the AirBeam sensors provided a stable and consistent measurement over a range of different wintertime meteorological and physical conditions, including the varying chemical composition and size distribution of PM. The high R^2 values demonstrate that the AirBeams have robust sensor-to-sensor precision, and when deployed at various community sites, the difference in concentrations among them is real and quantifiable.

Intercepts and slopes of regression computed for each AirBeam during the pre- and post-study collocation period are also presented in Appendix B. The standard deviation of the absolute value of the deviation of these slopes from the mean is 6.9% across 18 sites, when excluding one AirBeam that was consistently biased higher than all others. This finding shows how close the measurements from each AirBeam were to the collective average. This range of linear regression variables shows that the raw AirBeam measurements are typically closely intercomparable and within 15% of the AirBeam mean.

The generally robust precision of the measurements and the stable performance of the AirBeams in the pre- and post-study periods allowed for a normalization correction using the slopes and intercepts of regression against the mean. The formula for this normalization correction is *Normalized AirBeam = (Raw AirBeam – Intercept)/ Slope*. Averages of the pre- and post-study intercepts and slopes were used for the correction. For five of the AirBeams, the pre-study regressions were used for the correction factor for the study period, as a result of invalid data in the post-study period leading to a limited range of PM values. The slopes of regression remain very consistent during the two periods, indicating stable measurements and no significant changes in sensor response throughout the study period.

The normalization correction allows the network of AirBeam measurements to be intercomparable throughout the study period, with each AirBeam reporting a consistent value. The corrected AirBeam measurements can then be used to assess the accuracy of the AirBeam measurements, as well as examine the spatial and temporal variability of PM in the Sacramento metropolitan region throughout the study period.

3.4.2 Sensor Precision Results During the Study

During the study period, sets of three AirBeams were collocated at the T Street and Del Paso Manor sites. These measurements were also examined to assess precision. A stable linear relationship was seen for these sets of AirBeams throughout the study period, consistent with the pre- and post-study collocation data. For these two sets of three collocated AirBeams, during the entire study period, correlation R^2 values ranged from 0.987 to 0.995, within the range of the pre- and post-study collocation periods. Precision, of the collocated AirBeams at Del Paso Manor and T Street during December-January was estimated using the same formula used for HAPs in Section 3.1.1. The precision was between 4%-9%, indicating high precision. This is well within the 22% precision reported nationally for BAM FEM measurements, and similar to many FRM measurements, which have a range of 6% to 12% (U.S. Environmental Protection Agency, 2015b). This range of $PM_{2.5}$ values shows our confidence in the sensor precision during the study period. Figure 25 shows an example of an AirBeam to AirBeam comparison using raw data at the Del Paso Manor site (color coded to hours passed) that is representative of all collocated AirBeam pairs. This graphic confirms that during the study period, the AirBeams demonstrated a consistent bias relative to each other and there was no evidence of a drift in the measurements.

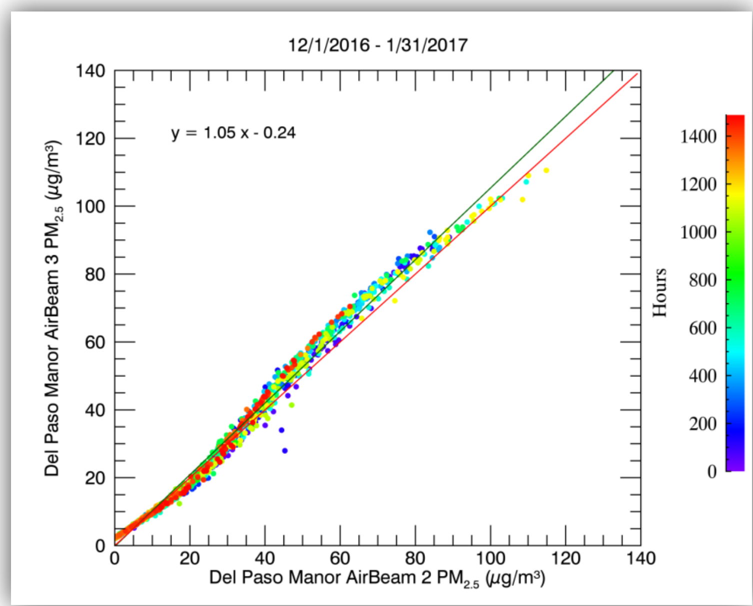


Figure 25. An example of AirBeam to AirBeam data from the Del Paso Manor site from December 2016 through January 2017. Hours label is hours since midnight on December 1, 2017.

3.4.3 Comparison of Sensor PM to Collocated BAM and FRM Measurements

During the study period, three AirBeams at the Del Paso Manor site were collocated with the BAM 1020 monitor, FRM, and meteorological measurements. Since the AirBeam measurements were corrected as discussed in section 3.4.1, the three AirBeams at Del Paso Manor presented nearly identical measurements, thus results from only one AirBeam at the site are presented. These collocated measurements provide an opportunity to examine sensor accuracy with respect to the BAM and FRM instruments, and how the AirBeam compares to these other measurements when considering changes in environmental conditions.

Figure 26 shows a comparison of the hourly normalized AirBeam values compared to the collocated BAM 1020 values at Del Paso Manor during the study period. The same data are presented in the four panels in the figure, but each panel is color coded based on a different meteorological condition measured at the Del Paso Manor station (RH, dew point temperature, temperature, and wind speed). RH values were quite high during the study period, with a value of 85% or greater during 65% of the measurement hours, and 90% or greater during 57% of the hours. Hourly dew point ranged from -2.7°C to 16.4°C, hourly wind speed ranged from 0 to 9 m/s, and hourly temperature ranged from -1.4°C to 17°C. This range is consistent with typical wintertime conditions in Sacramento, though there was significantly more rain than average.

The R^2 of the AirBeam and the BAM 1020 correlation is 0.601, which demonstrates moderate sensor accuracy. Figure 26 shows there was a range of AirBeam values for a given BAM concentration, spanning up to a factor of 3 higher (higher for the majority of the measurements). The deviation toward high AirBeam measurements relative to BAM measurements was generally during periods with dew point temperatures roughly greater than 5°C. However, under lower dew point conditions (roughly less than 5°C), the AirBeam and BAM instruments have approximately a 1:1 relationship. The dew point is an absolute, rather than relative, metric of how much water is in the atmosphere; relative humidity is relative to how much water the atmosphere can hold for a given temperature. Results here indicate that the amount of water in the atmosphere dictates the comparability of AirBeam measurements to measurements that do not rely on light scattering, such as the BAM's. This impact of high humidity on light-scattering or nephelometry-based instruments is a common phenomenon (Watson et al., 2001).

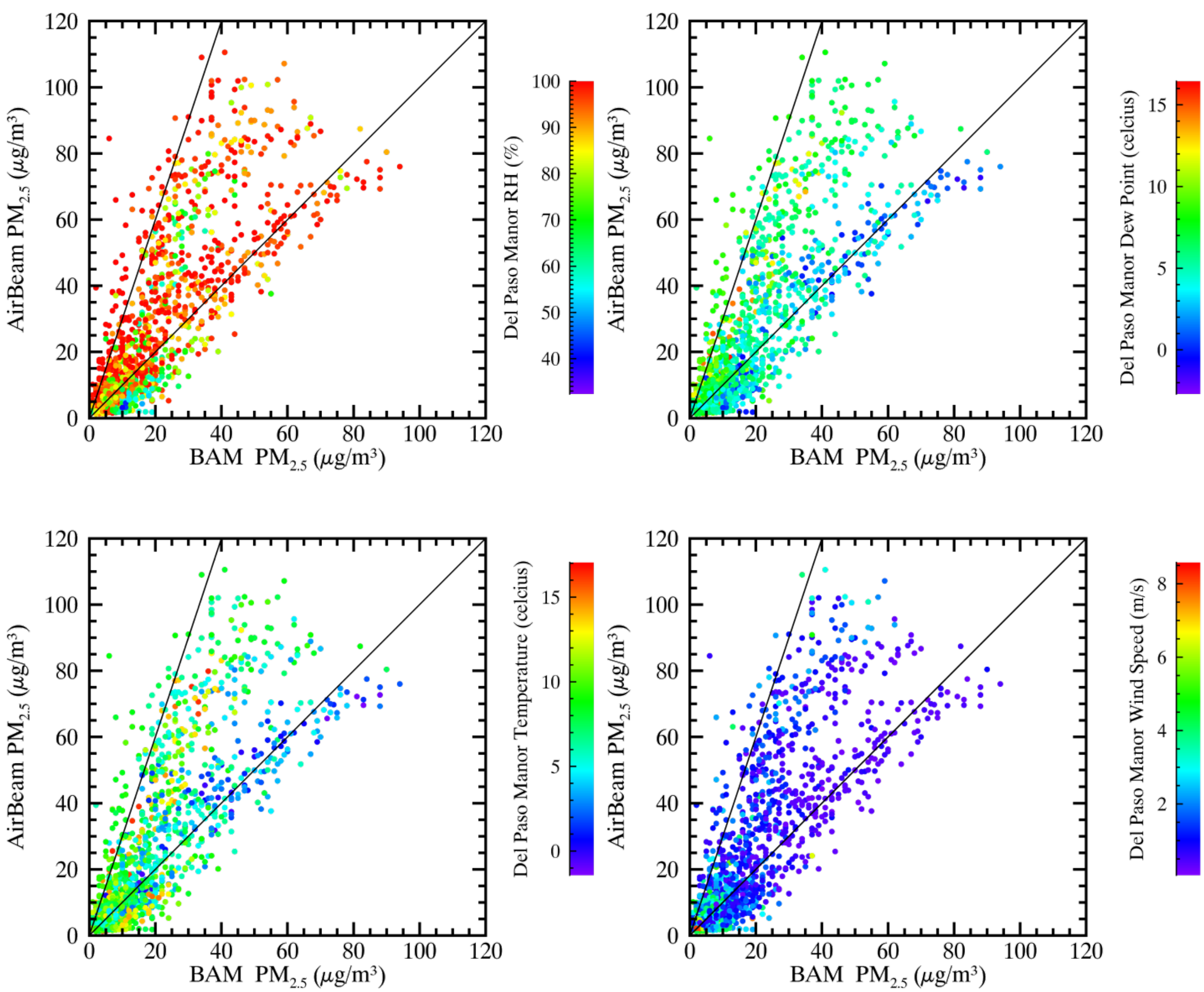


Figure 26. Comparison of the hourly $PM_{2.5}$ concentrations measured by the AirBeam and BAM instruments at the Del Paso Manor (DPM) site. The figures include 1:1 and 3:1 lines, and are colored by RH (upper left), dew point temperature (upper right), temperature (lower left), and wind speed (lower right) conditions.

Daily average values are also important to consider since regulatory National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ include a 24-hour standard. Therefore, the AirBeam data were compared to the FRM values from the sequential filter sampler. Figure 27 shows the relationship between daily average AirBeam values and the collocated FRM values at Del Paso Manor during the study period. Figure 27 is again color coded for the different meteorological conditions measured at the Del Paso Manor station (RH, dew point temperature, temperature, and wind speed). The R^2 of the daily average AirBeam and FRM concentrations is 0.71. Similar to the BAM comparisons, higher AirBeam values relative to the FRM occurred during periods with higher dew points, confirming a relative bias of AirBeams compared to BAM and FRM.

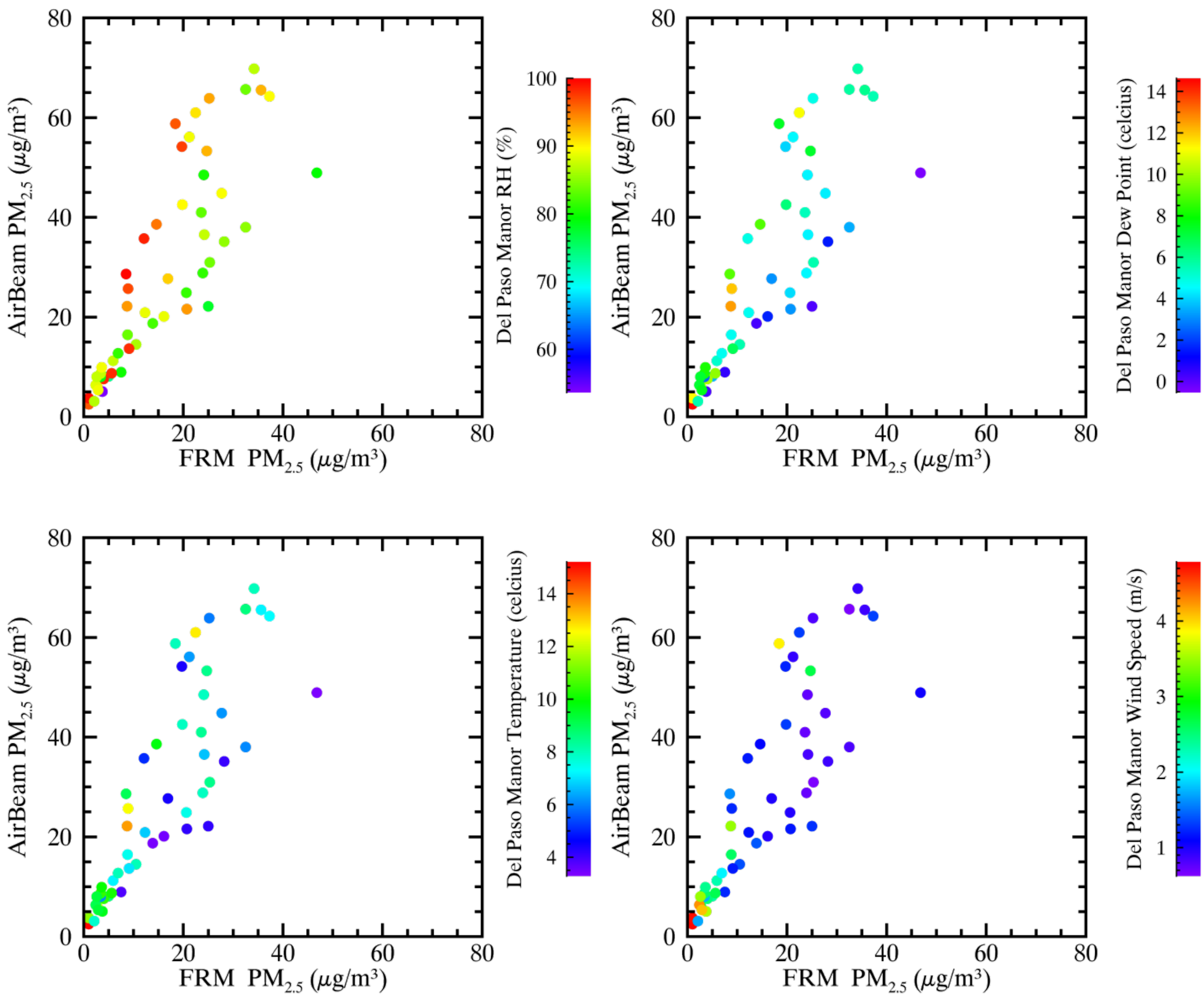


Figure 27. Comparison of the daily average $PM_{2.5}$ concentrations measured by the AirBeam and FRM instruments at the Del Paso Manor (DPM) site. The figures are colored by RH (upper left), dew point temperature (upper right), temperature (lower left) and wind speed (lower right) conditions.

3.4.4 Sensor PM Inter-Site Comparisons

PM had modest variability across sites during the study, as shown in a scatterplot matrix (**Figure 28**), a corresponding correlation matrix (**Table 18**), and a box plot of concentrations by site (**Figure 29**). R^2 values for inter-site comparisons ranged from 0.67 to 0.96. In comparing each site to all other sites, between any two given sites, PM had a correlation greater than 0.90. For example, the 13th Avenue, 24th Avenue, 64th Street, and 79th Street sites all have correlations greater than 0.90 with each other. Results may vary more or differently in other seasons when temperature, relative humidity, and emissions sources may be different. This study was not intended to assess the monitoring network coverage; rather, the focus was on spatial variability.

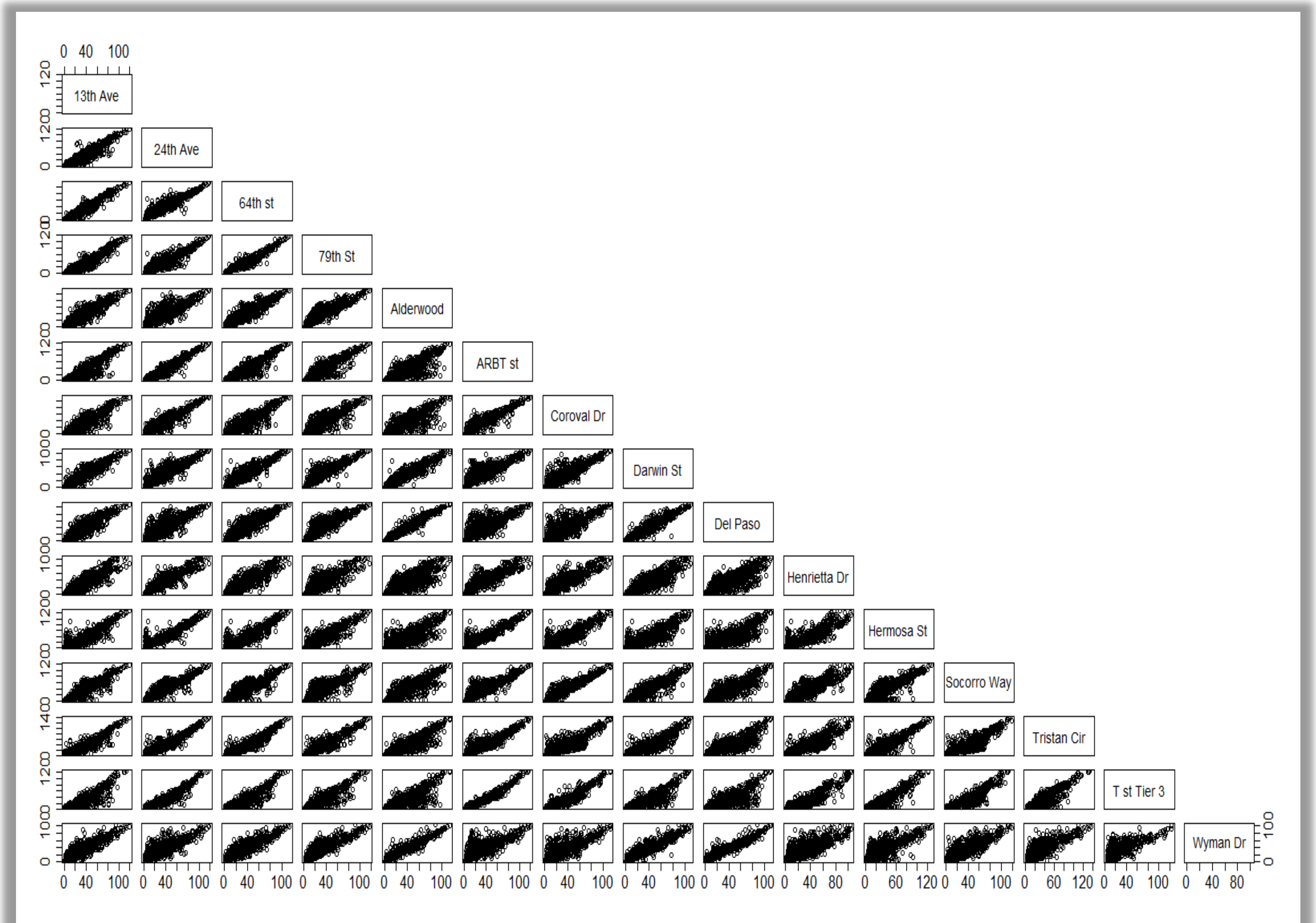


Figure 28. Scatterplot matrix of sensor PM measurements collected during the study period.

Table 18. Correlation coefficients (R^2) across all sensor PM measurements collected during the study period. The correlations are colored on a red-green scale, where red represents higher correlation (such as 1.00) and green represents lower correlation (such as 0.67).

Site Name	13th Ave.	24th Ave.	64th St.	79th St.	Alderwood Way	ARB T St.	Coroval Dr.	Darwin St.	Del Paso Manor	Henrietta Dr.	Hermosa St.	Socorro Way	Tristan Cir.	T St., Tier 3	Wyman Dr.
13th Ave.	1.00	0.90	0.95	0.91	0.88	0.84	0.82	0.90	0.87	0.83	0.83	0.87	0.89	0.79	0.84
24th Ave.	0.90	1.00	0.92	0.86	0.80	0.94	0.89	0.86	0.79	0.89	0.91	0.89	0.91	0.90	0.77
64th St.	0.95	0.92	1.00	0.94	0.88	0.86	0.82	0.90	0.87	0.84	0.86	0.86	0.90	0.83	0.85
79th St.	0.91	0.86	0.94	1.00	0.84	0.82	0.76	0.84	0.82	0.75	0.83	0.77	0.87	0.80	0.79
Alderwood Way	0.88	0.80	0.88	0.84	1.00	0.72	0.72	0.92	0.96	0.74	0.73	0.81	0.80	0.69	0.94
ARB T St.	0.84	0.94	0.86	0.82	0.72	1.00	0.90	0.80	0.72	0.85	0.90	0.85	0.87	0.95	0.70
Coroval Dr.	0.82	0.89	0.82	0.76	0.72	0.90	1.00	0.82	0.73	0.84	0.83	0.92	0.79	0.88	0.71
Darwin St.	0.90	0.86	0.90	0.84	0.92	0.80	0.82	1.00	0.93	0.81	0.78	0.89	0.81	0.77	0.90
Del Paso Manor	0.87	0.79	0.87	0.82	0.96	0.72	0.73	0.93	1.00	0.74	0.71	0.81	0.78	0.68	0.94
Henrietta Dr.	0.83	0.89	0.84	0.75	0.74	0.85	0.84	0.81	0.74	1.00	0.81	0.84	0.81	0.84	0.73
Hermosa St.	0.83	0.91	0.86	0.83	0.73	0.90	0.83	0.78	0.71	0.81	1.00	0.81	0.86	0.87	0.71
Socorro Way	0.87	0.89	0.86	0.77	0.81	0.85	0.92	0.89	0.81	0.84	0.81	1.00	0.81	0.83	0.79
Tristan Cir.	0.89	0.91	0.90	0.87	0.80	0.87	0.79	0.81	0.78	0.81	0.86	0.81	1.00	0.84	0.77
T St., Tier 3	0.79	0.90	0.83	0.80	0.69	0.95	0.88	0.77	0.68	0.84	0.87	0.83	0.84	1.00	0.67
Wyman Dr.	0.84	0.77	0.85	0.79	0.94	0.70	0.71	0.90	0.94	0.73	0.71	0.79	0.77	0.67	1.00

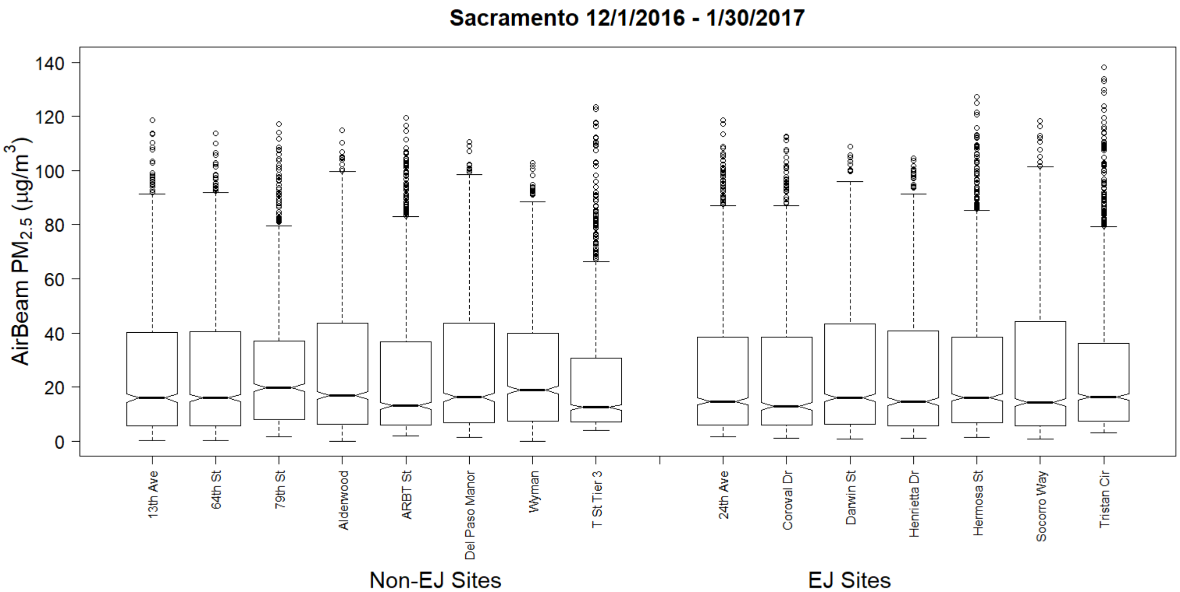
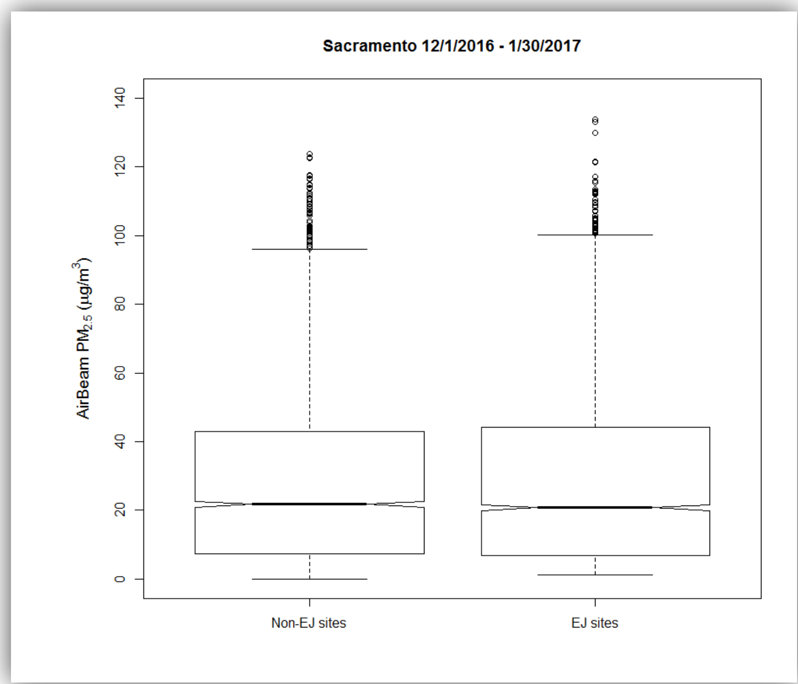


Figure 29. Notched box plot of sensor PM measurements collected during the study period, grouped by EJ and non-EJ sites. The notch indicates the median, the box indicates the interquartile range (IQR), whiskers indicate 1.5*IQR, and points beyond the whiskers are plotted individually.

As shown in Figure 29, there is some site-to-site variability. A Student's T-test comparison of the measurements from EJ communities to non-EJ communities found no statistically significant difference in the $PM_{2.5}$ levels (p value = 0.238). The non-parametric Pairwise Wilcoxon Rank comparison for the nine paired EJ and non-EJ sites show that for eight cases there was no statistically significant difference between the means (p value > 0.68); for one case (the T Street non-EJ site and the South Sacramento EJ site), there was a statistically significant difference in the means (p value = 0.00046, a difference of 1.5 $\mu g/m^3$). When the EJ sites are grouped together and compared to the grouped non-EJ sites, there was no significant difference in PM concentrations (similar to BC concentrations). Figure 30 shows the PM concentrations measured at all EJ and non-EJ sites. It also shows the concentrations recorded from the six AirBeams at the sites which also recorded HAP and BC measurements; these sites are used to represent the six different communities monitored in the study. There was some variation within the non-EJ sites (the T Street site had lower concentrations than the Del Paso Manor and Colonial Heights sites), while the EJ sites all had statistically similar concentration ranges.



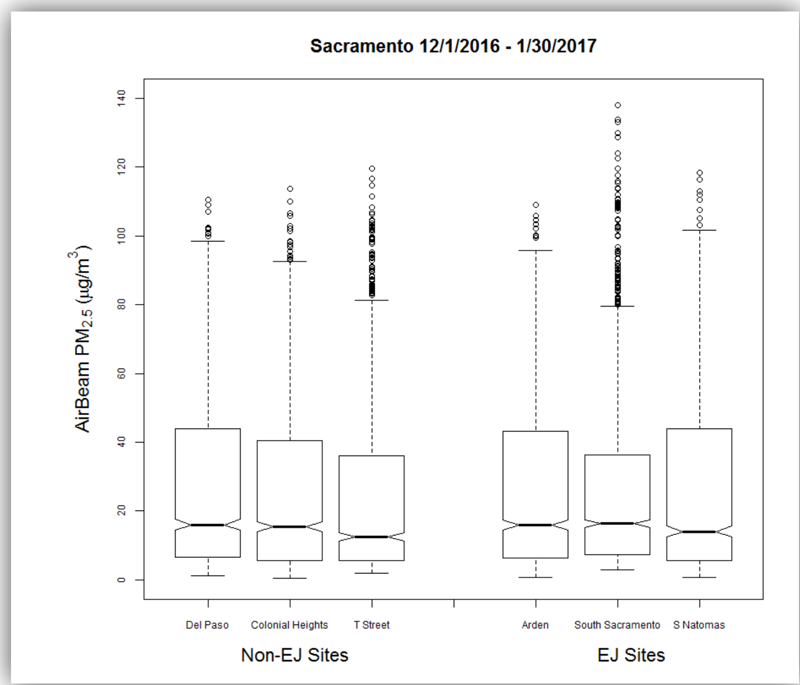


Figure 30 Notched box plot of sensor PM concentrations by all EJ and non-EJ sites (top), and by the six representative community sites (bottom). The notch indicates the median, the box indicates the interquartile range (IQR), whiskers indicate 1.5*IQR, and points beyond the whiskers are plotted individually. Del Paso is Del Paso Manor.

3.5 Comparison Among Measurements

3.5.1 Regression Comparisons of HAPs with Levoglucosan and BC

Regression statistics were examined at each site to see how BC_{wb} and levoglucosan concentrations related to each HAP, and how HAPs related to each other. Levoglucosan is directly emitted from wood burning and is thus the tracer used for wood burning. Consistent across all six sites, BC_{wb} and levoglucosan had little correlation with any HAP (i.e., $R^2 < 0.20$; see **Table 19**). This finding indicates that wood burning has little relation to HAPs at any site. As expected, carbon tetrachloride had little correlation with any other HAP ($R^2 < 0.12$), since its concentration levels are representative of global background concentrations. HAPs that are typically from fossil fuel combustion (benzene, ethylbenzene, m,p-xylene, toluene, 1,3-butadiene, 2,2,4-trimethylpentane) had high correlations among themselves at every site ($R^2 > 0.70$). This means that all of these species are from the same type of source, i.e., mobile source emissions.

Table 19. Matrix of median correlation coefficient (R^2) of HAPs, PM, and filter measurements (where available) across all six monitoring sites. Correlations greater than 0.70 are shown in **bold**.

Parameters	Acetonitrile	Acetylene	Acrolein	BC	BC_{ff}	BC_{wb}	Benzene	CCl4	Ethylbenzene	M,p-Xylene	Toluene	1,3-Butadiene	iso-octane	Levoglucosan
$PM_{2.5}$ (AirBeams)	0.13	0.16	0.00	0.09	0.12	0.05	0.18	0.05	0.18	0.15	0.19	0.24	0.18	0.02
Acetonitrile	N/A	0.17	0.03	0.10	0.09	0.07	0.47	0.01	0.36	0.33	0.35	0.37	0.36	0.21
Acetylene	0.17	N/A	0.00	0.11	0.05	0.12	0.53	0.12	0.46	0.43	0.43	0.54	0.43	0.07
Acrolein	0.03	0.00	N/A	0.07	0.05	0.06	0.02	0.06	0.00	0.00	0.00	0.02	0.00	0.11
BC	0.10	0.11	0.07	N/A	**0.71**	**0.84**	0.10	0.00	0.10	0.08	0.09	0.08	0.11	**0.85**
BC_{ff}	0.09	0.05	0.05	**0.71**	N/A	0.31	0.06	0.01	0.04	0.03	0.03	0.06	0.05	0.05
BC_{wb} (wood burning tracer)	0.07	0.12	0.06	**0.84**	0.31	N/A	0.09	0.00	0.11	0.09	0.10	0.06	0.11	**0.88**
Benzene	0.47	0.53	0.02	0.10	0.06	0.09	N/A	0.03	**0.80**	**0.78**	**0.84**	**0.87**	**0.78**	0.17
CCl4	0.01	0.12	0.06	0.00	0.01	0.00	0.03	N/A	0.06	0.06	0.06	0.08	0.07	0.00
Ethylbenzene	0.36	0.46	0.00	0.10	0.04	0.11	**0.80**	0.06	N/A	**0.97**	**0.90**	0.67	**0.90**	0.15
M,p-Xylene	0.33	0.43	0.00	0.08	0.03	0.09	**0.78**	0.06	**0.97**	N/A	**0.85**	0.68	**0.85**	0.13
Toluene	0.35	0.43	0.00	0.09	0.03	0.10	**0.84**	0.06	**0.90**	**0.85**	N/A	**0.72**	**0.91**	0.17
1,3-Butadiene	0.37	0.54	0.02	0.08	0.06	0.06	**0.87**	0.08	0.67	0.68	**0.72**	N/A	0.65	0.11
Iso-octane (fossil fuel tracer)	0.36	0.43	0.00	0.11	0.05	0.11	**0.78**	0.07	**0.90**	**0.85**	**0.91**	0.65	N/A	0.16
Levoglucosan (wood burning tracer)	0.21	0.07	0.11	**0.85**	0.05	**0.88**	0.17	0.00	0.15	0.13	0.17	0.11	0.16	N/A

3.5.2 Ratio:Ratio Plots

Ratio:ratio plots were used to help understand the relative contribution of wood smoke and fossil fuel combustion to HAPs, OC, EC, and $PM_{2.5}$. The relative importance of two sources can be found by plotting the ratio of each species relative to tracers of wood smoke (represented by BC_{wb}) or fossil fuel combustion (represented by 2,2,4-Trimethylpentane). High correlation in a ratio:ratio plot indicates there is little impact from the applied tracer on the species in question, whereas low correlation indicates a high impact from the tracer. Examples are given in Figures 31 and 32, which highlight the Benzene/toluene and acetylene/1,3-butadiene results These figures clearly indicate that there was little-to-no impact from wood burning on HAP concentrations. When divided by BC_{wb}, the HAPs are highly correlated on the ratio:ratio plots, but when divided by 2,2,4-Trimethylpentane, the results cluster together tightly. These relationships indicate that a singular source of emissions dominates the example species in the Figures. Similar results are seen for most of the hydrocarbons (benzene, toluene, ethylbenzene, acetylene, xylenes, and 1,3-butadiene). However, as seen in Figure 33, the oxygenated, nitrogenated, and chlorinated compounds such as acetonitrile and acrolein do not display this characteristic relationship when divided by either BC_{wb} or 2,2,4-trimethylpentane. This result indicates that these compounds are not associated with BC_{wb} or 2,2,4-trimethylpentane.

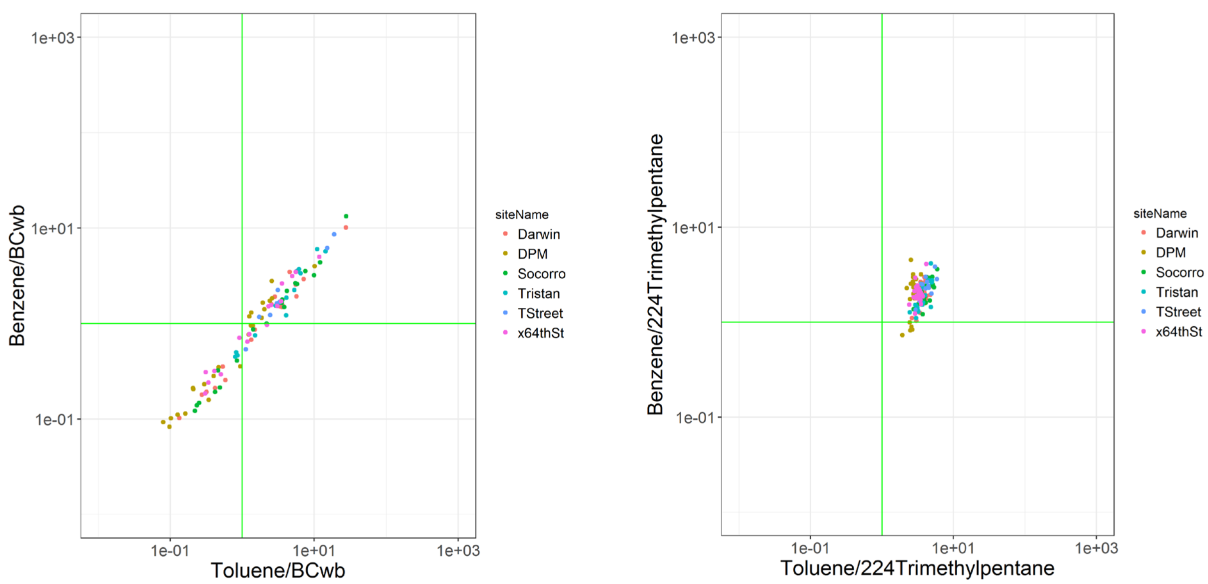


Figure 31. Ratio:ratio plot of benzene and toluene, divided by BC_{wb} (left) and 2,2,4-trimethylpentane (right).

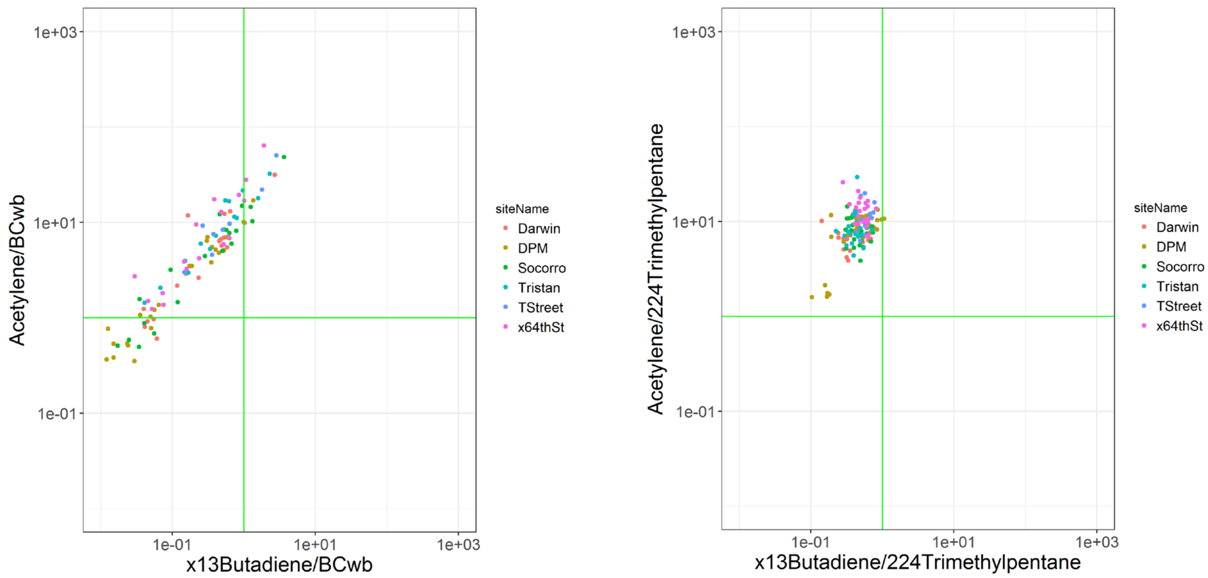


Figure 32. Ratio:ratio plot of acetylene and 1,3-butadiene, divided by BC_{wb} (left) and 2,2,4-trimethylpentane (right).

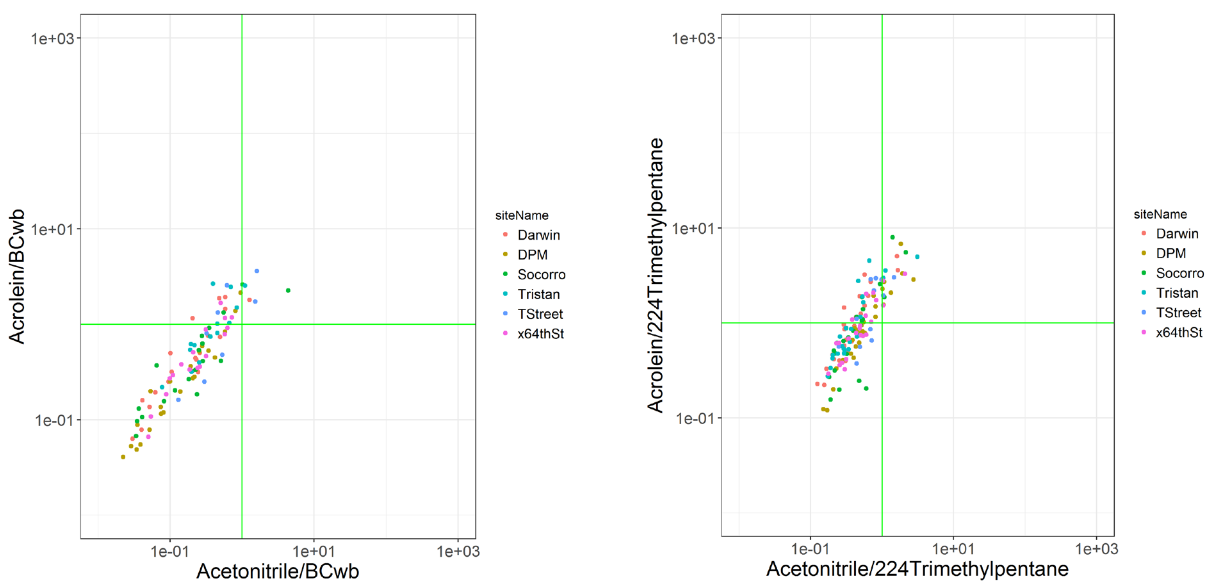


Figure 33. Ratio:ratio plot of acetonitrile and acrolein, divided by BC_{wb} (left) and 2,2,4-trimethylpentane (right).

3.5.3 Coefficient of Divergence Results

The COD metric shows the degree of regional or localized variability of each pollutant. COD results indicate that HAP concentrations were moderately homogeneous, while BC, BC_{ff}, and BC_{wb} were highly variable site-to-site. Figure 34 shows the average COD results by pollutant. As expected from the global homogeneity discussed previously, carbon tetrachloride had the lowest average COD across all sites (0.07). HAP CODs ranged from 0.18 (acetonitrile) to 0.28 (m,p-xylene), indicating some urban-scale variability across the study regime, but much less so than the primary BC pollutants, which appear to have high variability across the study zone. Notably, BC, BC_{ff}, and BC_{wb} had high COD values (0.36, 0.46, and 0.50), indicating community-scale variability that is much larger than PM (0.23) or HAPs.

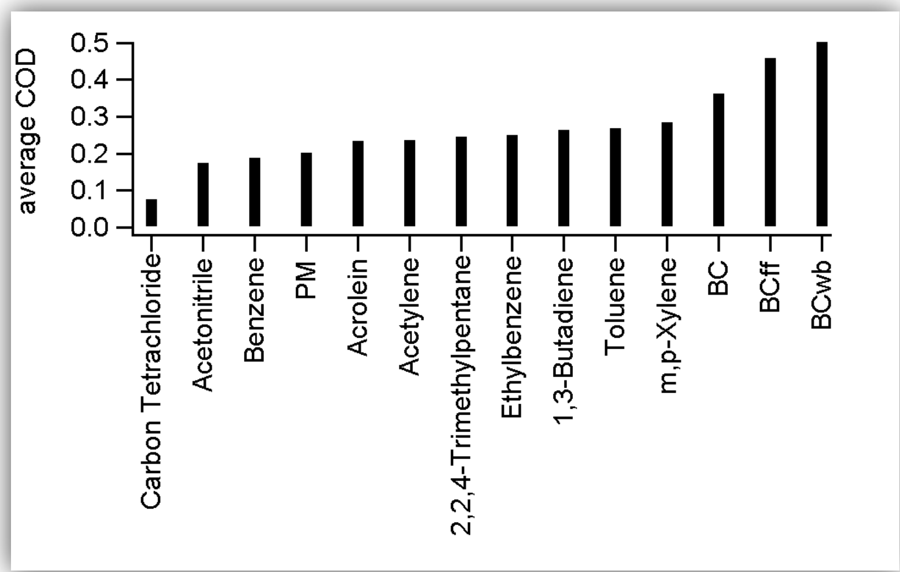


Figure 34. Average coefficient of divergence (COD) across measurement sites by pollutant.

3.5.4 Attribution of PM from Wood Burning via Aethalometer

Levoglucosan is a direct tracer for wood burning. It is typically collected via multi-hour filter measurements, so cannot be measured continuously; significant labor and equipment is required to collect and chemically analyze the filters. The Aethalometer provides a calculated value of wood burning on an hourly basis and can run with little maintenance at multiple sites, but requires validation that the wood burning calculation is correct. Both filter and Aethalometer measurements were collected at the Del Paso Manor, Tristan, and T Street sites in order to confirm that the Aethalometer BC_{wb} calculation is correct and to develop an equation to convert BC_{wb} to $PM_{2.5}$ from wood burning. If BC_{wb} has a strong relationship with levoglucosan, it can be used to determine wood burning PM concentrations from Aethalometer measurements. To assess how reasonable BC_{wb} was as an indicator of wood burning, levoglucosan was compared to BC_{wb} concentrations when the filters were collected, as shown in Figure 37. Correlations between the concentrations of the two species were generally high. At the Del Paso Manor site, which had the highest levoglucosan concentrations and was therefore most impacted by wood smoke, there was a very high correlation between levoglucosan and BC_{wb} (R^2=0.95). There were moderate correlations between BC_{wb} and levoglucosan concentrations at the Tristan (R^2=0.675) and T Street (R^2=0.803) sites.

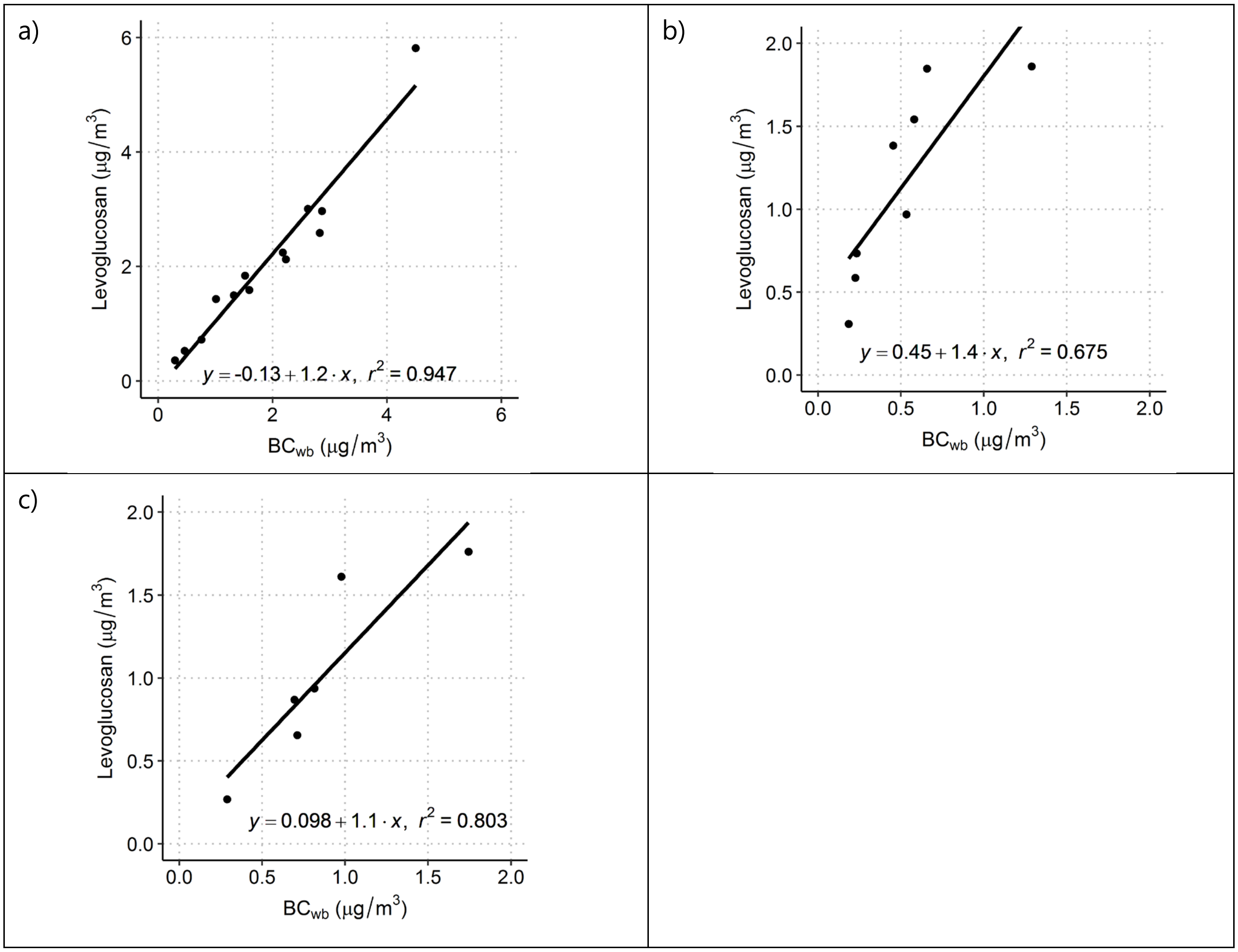


Figure 35. BC_{wb} (µg/m^3) concentrations compared to levoglucosan (µg/m^3) at the (a) Del Paso Manor; (b) Tristan; and (c) T Street sites.

Since there is high correlation between levoglucosan and BC_{wb}, the calculation of levoglucosan to wood burning PM can be adapted to calculate wood burning PM from BC_{wb}, by employing the regression result between levoglucosan and BC_{wb} at the very highly correlated Del Paso Manor site (Figure 36). The Del Paso Manor site was selected since it is the site with the highest levoglucosan (and thus wood burning) concentrations among the three sites with levoglucosan data. The regression results for Del Paso Manor in Figure 38 are *levoglucosan = 1.1 x* BC_{wb}.. Levoglucosan was converted to $PM_{2.5}$ from wood burning based on the literature-reported conversion factor discussed in Section 2.6. Thus, the calculation from BC_{wb} to wood burning PM is:

$$Wood\ burning\ PM = BC_{wb} \times 1.1 \times 7.35$$

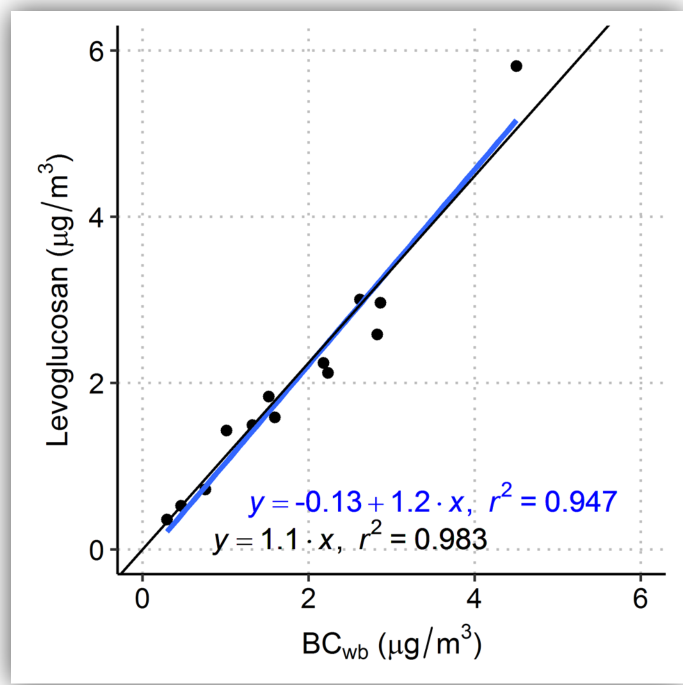


Figure 36. Linear regression for BC_{wb} versus levoglucosan concentrations (µg/m^3) at the Del Paso Manor site with the intercept term forced to zero. The non-zero intercept linear regression equation and line are shown in blue, and the equation with an intercept of zero and regression line are shown in black.

The median hourly concentration for wood burning PM at the Del Paso Manor site throughout the study period was 2.1 µg/m^3, twice as high as the other sites, which ranged from 1 to 1.3 µg/m^3 (Table 20). The large standard deviation relative to the concentrations at each site indicates that hourly concentrations are highly variable; e.g., at Del Paso Manor, the standard deviation is 10.8 µg/m^3, which is five times the median concentration. The Pearson correlation coefficient for hourly $PM_{2.5}$ from wood burning between sites ranged from 0.32 to 0.90, consistent with the high coefficient of divergence for BC measurements (Table 21). However, all sites except for T Street have a relatively high correlation (0.75 to 0.90) with each other, indicating that T Street BC patterns are different than at other sites, consistent with temporal BC patterns discussed in Section 3.3.2. The correlation coefficient for concentrations measured at the T Street site compared with other sites ranged from 0.32 to 0.41, indicating that concentrations of $PM_{2.5}$ from wood burning at the T Street site exhibited temporal patterns different from the other sites, possibly because it is relatively less residential than the other site areas.

Table 20. Median and standard deviation (SD) of the concentration of $PM_{2.5}$ from wood burning (µg/m^3) based on Aethalometer measurements. Summary statistics were calculated for December 2016 through January 2017.

Site	Median Concentration of $PM_{2.5}$ from Wood Burning (SD)
64th Street	1.3 (5.7)
Darwin	1.3 (7.3)
Del Paso Manor	2.1 (10.8)
Socorro	1.1 (6.1)
Tristan	1 (3.4)
T Street	1.1 (3.1)

Table 21. Correlation coefficient (R^2) of $PM_{2.5}$ estimated from wood burning via Aethalometer among sites.

	64th St	Darwin	Del Paso Manor	Socorro	Tristan	T Street
64th St	1.00	0.85	0.90	0.83	0.75	0.37
Darwin	0.85	1.00	0.89	0.86	0.78	0.36
Del Paso Manor	0.90	0.89	1.00	0.82	0.77	0.32
Socorro	0.83	0.86	0.82	1.00	0.75	0.41
Tristan	0.75	0.78	0.77	0.75	1.00	0.33
T Street	0.37	0.36	0.32	0.41	0.33	1.00

3.5.5 Source Attribution of HAPs with PMF

PMF was used to apportion the HAPs by basic source type. Figure 37 shows the distribution of each HAP by PMF source type; "burning" is identified with the tracer BC_{wb}, and "mobile sources" are identified with the tracer iso-octane. Table 22 shows the normalized relative contribution of each factor by site, and by EJ and non-EJ samples. Most HAPs have little influence from burning emissions, which is consistent with the ratio:ratio plots and correlation analyses shown earlier. Rather, most of ethylbenzene, benzene, m,p-xylene, toluene, 1,3-butadiene, acetylene and iso-octane are predominantly attributed to mobile source emissions. Carbon tetrachloride, acetonitrile, and acrolein are predominantly attributed to other sources and global or regional background concentrations, rather than locally emitted sources. For example, carbon tetrachloride is not emitted in the U.S. but it has a persistent background level because of its longevity in the atmosphere. The burning source type is highest at the Del Paso Manor site, and overall in non-EJ areas; mobile source contributions are highest at the T Street site, and overall slightly higher in EJ areas, but not significantly so, at a 95% confidence level. "Other" sources are higher at the Darwin and Socorro sites, and at EJ locations overall, as a result of the higher concentrations of acetonitrile and acetylene at these locations. Overall, results are consistent with the ratio:ratio plots, correlation analyses, and other analyses presented in earlier sections; which indicates wood burning is not a major source of HAPs at any site.

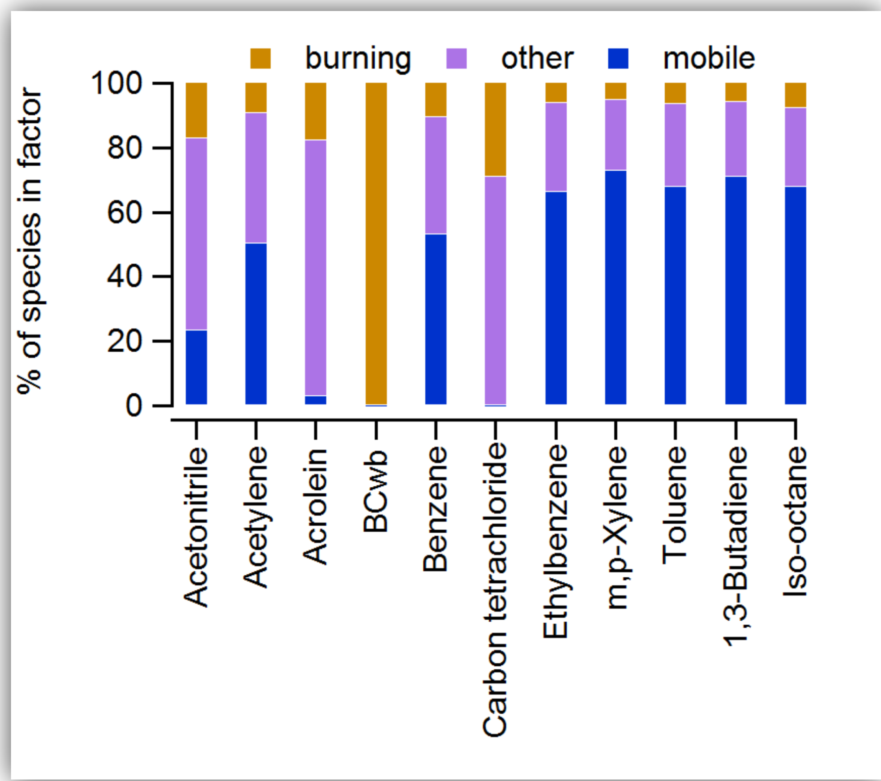


Figure 37. Percentage of each species in burning, other, and mobile-source PMF factors.

Table 22. Normalized contributions of each factor by site and by EJ and non-EJ sites. The average of all values in a given factor is 1.

Site	Burning	Other	Mobile
Darwin	1.18	1.41	1.04
Del Paso Manor	1.58	0.53	0.87
Socorro	1.07	1.47	0.89
Tristan	0.43	0.95	1.17
T Street	0.36	0.83	1.23
64th St	0.99	0.82	0.93
All EJ sites	0.75	1.21	1.03
All Non-EJ sites	1.12	0.70	0.96

3.6 Comparison of PM Results to Emissions Inventory (EI)

PM results were compared to the EI provided by the California Air Resources Board. The AirBeam $PM_{2.5}$ concentrations exhibited statistically significant spatial clustering (Global Moran's I statistic of 1.0, $p < 0.005$), with generally higher $PM_{2.5}$ concentrations in the northeast section of the study area and lower concentrations south of the American River and in western South Natomas (**Figures 38 and 39**). This pattern is also observed in the EI data set. The relationship between the measured concentrations of $PM_{2.5}$ and the emissions inventory (**Figures 40 and 41**) showed a higher R^2 for weekend days than weekdays. Weekend days showed more variability in measured $PM_{2.5}$ across sites (SD = 1.9 $\mu g/m^3$) than weekdays (SD = 1.3 $\mu g/m^3$). The larger differences between sites on weekend days may account for the stronger observed relationship with the emissions inventory on those days. The modestly high correlation indicates that overall, the EI appears to capture the spatial variability in PM emissions in each grid cell. This indicates that the EI tends to be correct in the relative amount of PM emissions in each grid cell. The two cells that had the largest disagreement with the measurements were the cells containing the Tristan and Socorro sites. The EI may be incorrect for these grid cells, or the location of the monitors may not be completely representative of the entire grid cell.

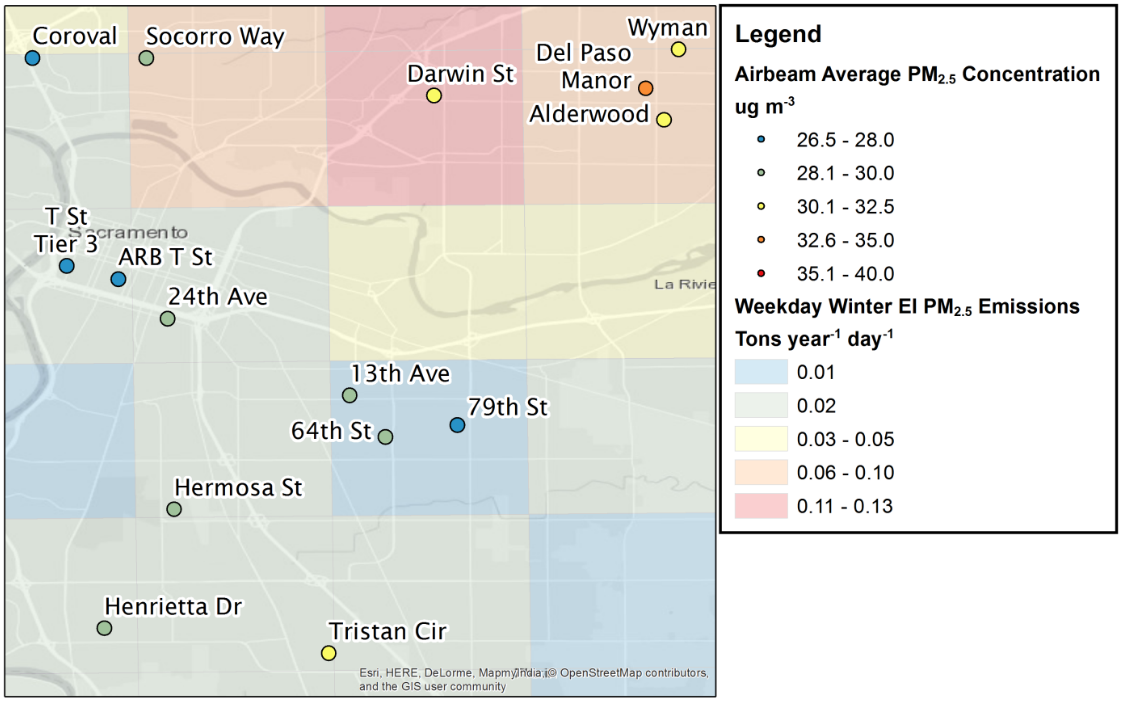


Figure 38. Map of 4-by-4 km gridded winter weekday $PM_{2.5}$ emissions and average AirBeam $PM_{2.5}$ concentrations.

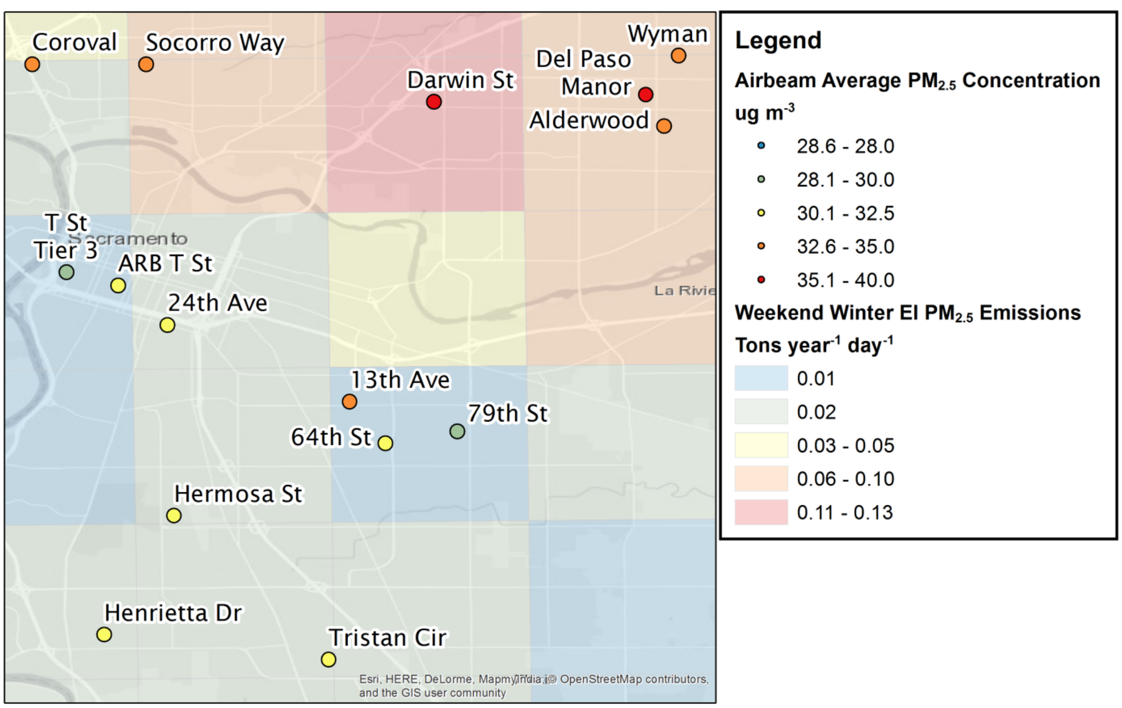


Figure 39. Map of 4-by-4 km gridded winter weekend $PM_{2.5}$ emissions and average AirBeam $PM_{2.5}$ concentrations.

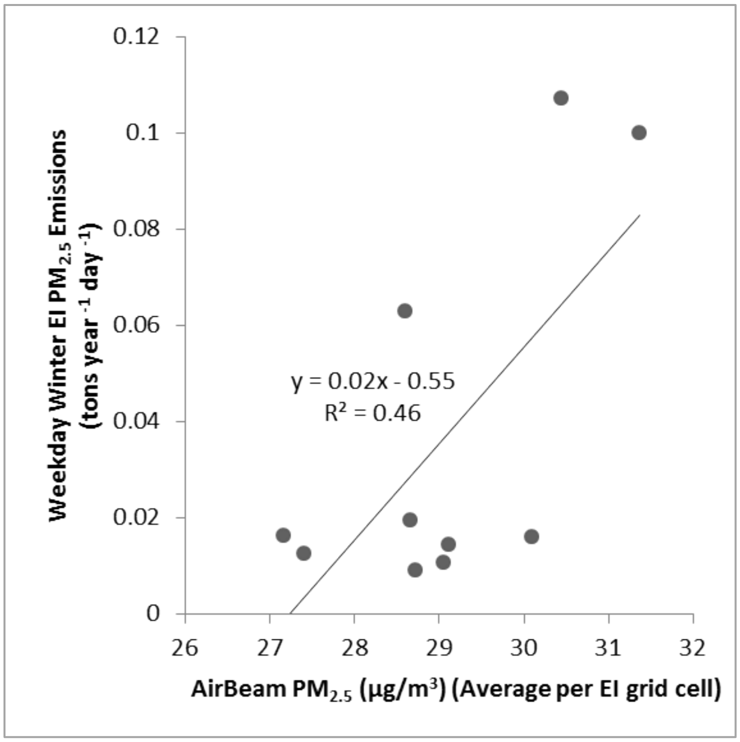


Figure 40. Comparison of gridded winter weekday $PM_{2.5}$ emissions and average weekday AirBeam $PM_{2.5}$ concentrations in the grid cell from December 2016 through January 2017.

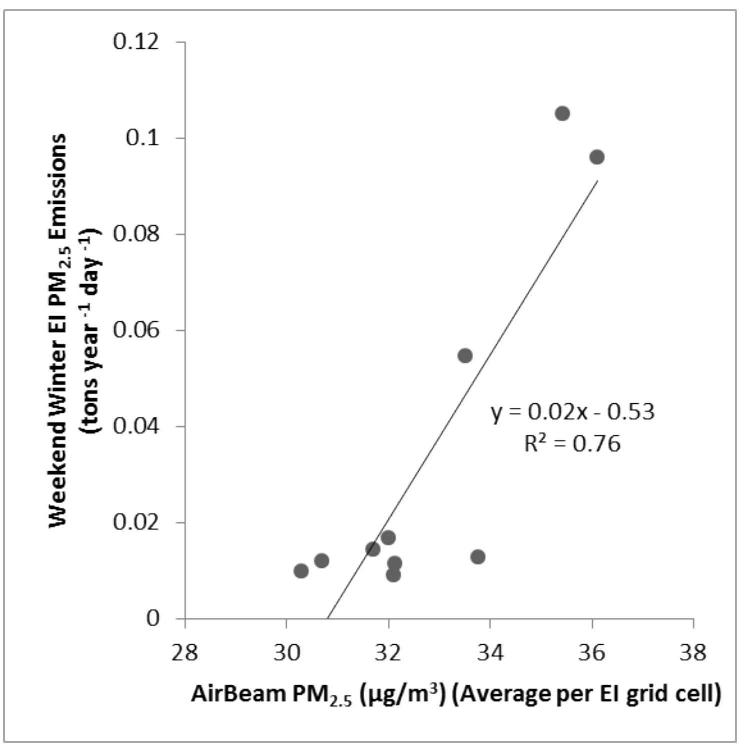


Figure 41. Comparison of gridded winter weekend $PM_{2.5}$ emissions and average AirBeam $PM_{2.5}$ concentrations in the grid cell from December 2016 through January 2017.

4. Community Survey Findings

4.1 Summary of Findings

The following excerpts are adapted from the September 2017 "Measuring Toxics from Wood Smoke: Community Monitoring Survey Results" report prepared by Meta Research, Inc. The full report is provided as Appendix A. One of the main objectives of the survey was to understand the types of burning devices and the frequency of use of such devices in EJ and non-EJ communities.

> Overall, general ownership trends show indoor fireplaces as the most prevalent device. Ownership of the other devices is infrequent, variation between EJ and non-EJ groups is nearly absent, and only slight variation is found between the communities. Because prevalence of devices other than indoor fireplaces is low among all communities, analyses of wood burning activity for those devices is tenuous.
>
> Overall, in terms of device ownership:
>
> - The most commonly owned device is an indoor fireplace, owned by 79% of all respondents.
> - Device ownership rates are nearly synonymous between EJ and non-EJ respondent groups. An indoor fireplace is the most frequently owned device by both groups.
> - Respondents in the T Street (non-EJ) community are less likely to own an indoor fireplace than those in the other communities (63% vs 79% avg.). Instead, these respondents are more likely to own outdoor wood burning fire pits (27% vs 15% avg.).
> - EJ Community respondents are significantly less likely to own more than one device (6%) compared to non-EJ Community respondents (10%).
> - A small percentage of respondents in each community own more than one device and Del Paso Manor (non-EJ) residents stand out as substantially more likely to own multiple devices (12% vs 8% avg.).
>
> In general, respondents who burn with their device are doing so between one and two days per week. This frequency increases the more devices a respondent owns. Wood or pellet stoves are used most frequently out of the three indoor devices. Indoor fireplaces are used least frequently in all communities.
>
> While significant differences between communities are nearly absent, some distinctions can be made at the community level. Of all respondents owning an indoor fireplace, the non-EJ community is burning (0.35 days per week) significantly more than the EJ community (0.23 days per week). Among respondents who burn with their fireplace inserts, those in non-EJ communities are burning (1.83 days per week) significantly more often than respondents in EJ communities (1.20 days per week). In summary:

- Respondents who burn with their device are doing so between one and two days per week. This frequency increases the more devices a respondent owns.
- Among all respondents, owners of wood or pellet stoves burn more frequently than owners of indoor fireplaces or fireplace inserts. The same is true when comparing the EJ and non-EJ communities.
- Between EJ and non-EJ communities, and including respondents who did not burn with their device at all, only use of indoor fireplaces results in a statistically significant difference in burning activity. Non-EJ community members more frequently use their indoor fireplaces (0.35 days per week) than EJ community members (0.23 days per week).
- After removing respondents who did not burn with their device at all, indoor fireplace use becomes nearly equal between EJ and non-EJ community members.

These results from Meta Research's report mean that there is no significant difference between EJ and non-EJ areas in:

- Device ownership (fireplace, stove, etc.)
- Fraction of homes burning with fireplaces
- Fraction of homes burning day and night
- Fraction of homes burning only at night
- Fraction of homes with certified burning devices
- Fraction of homes burning on CBYB days

The only significant differences are that non-EJ areas burn with an indoor device more often than EJ areas do, and thus have a higher relative number of burn days than EJ areas. The relative number of burn days was calculated by how often each respondent used a device, e.g., if a respondent used the device one day a week, the relative number of burn days per week would be 1.

4.2 Comparison of Survey Results to Ambient Data

Table 23 summarizes survey and ambient HAPs and BC_{wb} results. In terms of burning devices and burning activity, non-EJ areas have more device usage than EJ areas and thus a significantly higher relative number of burn days. This difference in the number of burn days likely means there are more emissions from wood burning in non-EJ areas, which corresponds with the significantly higher observed BC_{wb} in non-EJ areas. However, HAPs have an opposite relationship, as in the EJ areas where less wood burning occurs than non-EJ areas, multiple HAPs are higher. . These results support all other analyses of the ambient data showing that wood burning has little impact on ambient HAP concentrations.

Table 23. Summary of survey results by community and by EJ and non-EJ area, plus average concentrations of HAPs and BC_{wb} by EJ and non-EJ area. **Bold** indicates significant differences; yellow indicates which value is higher where there is a significant difference; "question" indicates the survey question from which the data are derived (Appendix A).

Metric	Arden	South Natomas	South Sacramento	Del Paso Manor	T St	Tahoe Park	EJ	Non-EJ
Fraction of homes with fireplace or insert (question S3)	80	78	79	83	63	77	80	79
Fraction of homes with any indoor device (question S3)	89	88	93	96	80	91	91	89
Fraction of homes with wood or pellet stove (question S3)	5	2	8	9	0	6	7	8
Fraction of homes with only outdoor burning (question S3)	11	11	5	3	20	9	7	5
Fraction of homes with outdoor & indoor burning (question S3)	n/a	n/a	n/a	n/a	n/a	n/a	92	91
Relative burn days with indoor fireplace or insert (question S3x4.0a;x4.1a)	n/a	n/a	n/a	n/a	n/a	n/a	**0.27**	**0.43**
Relative burn days with wood or pellet stove (question S3x4.2a)	n/a	n/a	n/a	n/a	n/a	n/a	0.48	0.7
Relative burn days with any indoor device (question S3x4.0,4.1,4.2)	0.41	0.27	0.31	0.51	0.41	0.44	**0.31**	**0.48**
Of burners, fraction of homes burning at night w indoor fireplace (question 4.0b)	n/a	n/a	n/a	n/a	n/a	n/a	67	79
Of burners, fraction of homes burning day w indoor fireplace (question 4.0b)	n/a	n/a	n/a	n/a	n/a	n/a	10	9
Of burners, fraction of homes burning day+night w indoor fireplace (question 4.0b)	n/a	n/a	n/a	n/a	n/a	n/a	19	9
Of burners, fraction of homes burning at night with fireplace or insert (question S3x4.0b)	n/a	n/a	n/a	n/a	n/a	n/a	76	57
Of burners, fraction of homes burning at night with wood or pellet stove (question S3x4.0b)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Fraction of homes burning with certified device (question 4.0c)	n/a	n/a	n/a	n/a	n/a	n/a	34	28
Fraction of homes burning_indoor fireplace (questions 5.2 & 5.4)	40	29	25	42	42	29	**28**	**38**
Fraction of homes burning on Check Before You Burn days (question 5.2 & 5.4)	n/a	n/a	n/a	n/a	n/a	n/a	46	47

Metric	Arden	South Natomas	South Sacramento	Del Paso Manor	T St	Tahoe Park	EJ	Non-EJ
Average Concentrations by EJ and non-EJ Area								
1,3-Butadiene µg/m^3							0.18	0.16
2,2,4-Trimethylpentane µg/m^3							**0.37**	**0.31**
Acetonitrile µg/m^3							0.14	0.14
Acetylene µg/m^3							2.99	2.92
Acrolein µg/m^3							0.27	0.26
Benzene µg/m^3							**0.65**	**0.58**
Carbon Tetrachloride µg/m^3							0.09	0.09
Ethylbenzene µg/m^3							**0.20**	**0.18**
m,p-Xylene µg/m^3							**0.64**	**0.53**
Toluene µg/m^3							**1.34**	**1.03**
BC_{wb} µg/m^3							**0.41**	**0.48**

5. Conclusions and Recommendations

5.1 Conclusions

This study quantified concentrations of HAPs in various communities in Sacramento; determined to what degree wood smoke contributes to HAPs in these communities; and provided understanding into whether EJ communities are disproportionately impacted by wood smoke HAPs.

Impacts of HAPs on EJ communities:

- Concentrations of six HAPs (benzene, toluene, ethylbenzene, m,p-xylene, iso-octane, and acrolein) and BC_{ff} were significantly higher at EJ sites compared to non-EJ sites.

Wood smoke contributions to HAPs in Sacramento communities:

- Even though wood smoke emissions can contribute to HAPs, results consistently showed that wood burning has little influence on the ambient levels of HAPs in this study, and that fossil fuel combustion is the main source of HAPs.
- All analyses (temporal, ratio:ratio, source apportionment, etc.) produced the same conclusion, which provides confidence in the results.

Characterization of HAPs concentrations:

- Average concentrations of motor vehicle-related hydrocarbons (benzene, toluene, ethylbenzene, xylenes, 2,2,4-trimethylpentane [iso-octane], and 1,3-butadiene) at Sacramento sites are above the 95^{th} percentile compared to the annual average at sites in the United States. However, the relatively high concentrations reported here should not be over-interpreted in comparison with national ranges because samples were collected on only a handful of days.
- Concentrations of other HAPs, such as carbon tetrachloride, acetonitrile, and acrolein, were closer to concentrations seen at other U.S. monitoring sites; for example, carbon tetrachloride concentrations were typical of global background levels.

Wood smoke concentrations in Sacramento communities:

- BC_{wb} had a very high correlation with collocated measurements of levoglucosan (R^2 across three sites of 0.68 to 0.95), on the high end of reported literature values, indicating that BC_{wb} was a robust indicator for wood burning in Sacramento. Thus, Aethalometer BC_{wb} data could be used from all sites to assess wood burning contributions.
- BC and BC_{wb} concentrations were highest at Del Paso Manor.
- At the two Tier 1 monitoring sites (Del Paso Manor and T Street), wood burning was 29%-39% of the total $PM_{2.5}$ on nights when filters were collected.

- Spatially, wood burning PM is well distributed across Del Paso Manor, T Street, and Tristan during daytime, and highest around Del Paso Manor during nighttime.
- At all sites, Stage 1 and 2 burn days had higher concentrations of BC, BC_{wb}, and BC_{ff} compared with "legal to burn" days. This is expected, since Stage 1 and 2 days are called because the meteorology is conducive to higher $PM_{2.5}$ concentrations; these results cannot be used to assess the effectiveness of the Stage 1 or 2 level alerts, since the possible amount of concentrations without these alerts is unknown.

Impacts of wood smoke on EJ communities:

- BC_{wb} concentrations were significantly higher at non-EJ sites than EJ sites, while total PM was not significantly different between EJ and non-EJ sites.
- The only significant differences in the phone survey results between EJ and non-EJ areas are that non-EJ areas burn with an indoor device more often than EJ areas do, and non-EJ areas thus have a higher relative number of burn days than EJ areas.

Other key findings:

- PM concentrations were not significantly different between EJ and non-EJ sites.
- Overall, the emissions inventory appears to capture the spatial distribution of PM emissions, with observed PM concentrations showing a moderate correlation with gridded emissions inventory data (R^2=0.76 for weekends).
- The AirBeams demonstrated very high sensor-to-sensor precision during the pre-and post-study collocation periods, with R^2 values ranging from 0.98 to 0.999. This means that the AirBeam sensors provided a stable and consistent $PM_{2.5}$ measurement over a range of different wintertime meteorological and physical conditions, including the varying chemical composition and size distribution of PM. It also means that differences in concentration between them are real and quantifiable. In addition, no drift was observed during this study.
- The 1-hr PM values from the AirBeam and the BAM 1020 correlate modestly (R^2 = 0.60), demonstrating moderate sensor accuracy, typical of well-performing sensors.

Though wood burning was not a significant source of HAPs, it was a significant source of $PM_{2.5}$, and was highest at a non-EJ site (Del Paso Manor). While not a goal of the study, modern sensor technology was successfully used to gain more spatial coverage of PM concentrations at the community level; this amount of spatial coverage is difficult to achieve using traditional instruments.

5.2 Recommendations

Recommendations for SMAQMD outreach include the following.

- While HAPS from wood smoke do not significantly contribute to the overall risk, wood smoke still makes up a critical component of wintertime $PM_{2.5}$ in Sacramento County. Studies have shown that exposure to $PM_{2.5}$ causes adverse health effects such as decreased lung function and premature death. Therefore, it is critical for SMAQMD to continue to inform communities about wood smoke pollution and to motivate behavior change to reduce wood smoke pollution.

- There is a high awareness of the CBYB program in both EJ and non-EJ areas. SMAQMD may wish to consider targeting outreach to non-EJ areas where residents are unaware of the program and tend to burn more frequently; this may include changing the message or message platform depending on each group.
- The messaging and outreach about wood burning may need to be enhanced to target specific times of day, before holidays, etc., to gain a higher rate of compliance with Rule 421/CBYB, since BC_{wb} concentrations were highest on Christmas Eve.
- The percentage of people burning wood is small in both EJ and non-EJ areas, so identifying ways to better inform those who do burn is important, e.g., targeted, direct outreach into communities with characteristics similar to Del Paso Manor's. This non-EJ community was found in this study to have a higher frequency of burning than other areas, so identifying other communities with similar characteristics could reduce wood burning contributions in those communities as well.
- SMAQMD may wish to use available census-tract level information to better understand socioeconomic patterns in non-EJ areas with a higher frequency of burning to identify which groups may need targeted outreach to reduce their burning.
- SMAQMD may wish to conduct community outreach with low-cost sensors to build awareness about particle pollution. Community engagement will be important to the District as it moves forward to build stronger community relationships in support of District pollution reduction programs.

Recommendations for possible future work that builds on the work presented here are provided below.

- Using data collected here, develop statistical or machine learning models to improve existing air quality forecasting models.
- Develop a real-time wood burning PM calculation using Aethalometer data from Del Paso Manor, and use this in air quality forecasting and outreach.
- In areas where the EI predicts high PM, or where the ambient/EI comparison was not as good as in other areas, conduct additional community monitoring to better understand within-community variability and whether the EI estimates are low/high.
- Repeat PM or BC measurements for another winter to understand how consistent results are from year to year, and to further understand the reliability of the EI.
- Conduct a similar experiment for ozone in the summer, but use a larger spatial extent to better capture the variation in the region.
- Perform mobile monitoring of PM and BC in communities to identify whether there are "hot spots."

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Appendix A. Measuring Toxics From Wood Smoke: Community Monitoring Survey Results

Included is the final survey report prepared by Joseph Hanson of Meta Research, Inc., published September 11, 2017.

Measuring Toxics From Wood Smoke: Community Monitoring Survey Results

FINAL REPORT - 09/11/2017

Survey made possible through a U.S. Environmental Protection Agency grant provided to the Sacramento Metropolitan Air Quality Management District

Joseph Hanson
META RESEARCH, INC. | 2012 H Street, Sacramento, CA 95811 | (916) 325-1224

Contents

Project Details

Background

The mission of the Sacramento Metropolitan Air Quality Management District (SMAQMD) is to achieve state and federal clean air goals by leading the Sacramento region in protecting public health and the environment through innovative and effective programs, dedicated staff, community involvement and public education. The District's winter "Check Before You Burn" program is designed to reduce the amount of particulate matter (PM) pollution in Sacramento County that results from burning solid fuels (e.g. wood, pellets, or manufactured logs) in fireplaces, fireplace inserts, wood stoves, and outside fire pits and chimineas.

The SMAQMD received a grant from the U.S. Environmental Protection Agency (U.S. EPA) to improve its general understanding of issues concerning hazardous air pollutants (HAPs) from sources such as wood smoke. A key component was to gather information to enhance its capability to address any environmental justice (EJ) issues from exposure to PM and HAPs. Residential wood smoke is the main source of wintertime PM in Sacramento; and it is strongly suspected to be the main source of some HAPs, including acetaldehyde, acrolein, acetonitrile, and naphthalene.

The grant project involves (1) collecting ambient measurements of HAPs, wood smoke markers, and particulate matter (PM); (2) performing community surveys to gather information on wood burning activities (reported here); (3) analyzing the ambient data and community survey data (in combination with existing emission inventories) to quantify pollutant concentrations, their interurban (EJ versus Non-EJ) variations, and the interurban variations of wood burning activities; and (4) outreach to disadvantaged communities and other stakeholders on any EJ concerns that the study may illuminate related to wood burning and/or HAPs.

Objectives

The current study was designed in compliance with these goals. The main purpose of the community monitoring survey is to understand wood burning behavior and other factors that may influence exposure to wood smoke HAPs. Specifically, the objectives of the survey are to:

- Assess wood burning activity;
- Evaluate wood burning activity by type of device used to burn;
- Compare wood burning activity between EJ and Non-EJ neighborhoods;

Terminology

Throughout this report, reference is made to the surveyed EJ and Non-EJ neighborhoods. For simplicity, when discussing the neighborhoods combined into their corresponding EJ or Non-EJ parent category, the term "community" is used. When discussing results by neighborhood, the term "neighborhood" is used. That is, the Arden, South Natomas and South Sacramento *neighborhoods* belong to the EJ *community,* while the Del Paso Manor, T Street, and Tahoe Park-Colonial Heights *neighborhoods* belong to the Non-EJ *community.*

Methodology

Listed sample telephone interviews were completed with 900 (444 EJ; 456 Non-EJ) Sacramento County residents who owned a wood or pellet burning device (other than an outdoor barbecue) either inside or outside their home. The sample frame was provided by Sonoma Technology, Inc. (STI) in the form of address lists separated by EJ and Non-EJ status, based on the EPA's EJSCREEN tool[1]. These addresses were matched with listed landline and mobile phone numbers, then selected at random for interviewing.

The margin of error associated with a sample of 900 completed interviews is +/- 3.3% at the 95% confidence level. That is, we are 95% sure that the true population parameters lie within +/- 3.3% of the sample statistics. For example, if a response category to a question were chosen by 50% of sample respondents, we would be 95% sure that if the entire county population were surveyed, that same response category would be selected by 46.7%-53.3% of all residents (50% +/- 3.3%).

For the EJ community, at 444 completed interviews, the margin of error at the 95% confidence level is +/- 4.7% while the Non-EJ community, with 456 completed interviews, is +/- 4.6%.

[1] See Appendix C for a map of targeted locations. Del Paso Manor addresses which were included after interviewing began when completion rates indicated a need to identify more addresses in order to meet the 900 respondent completion requirement.

Figure I: Sampling Error	EJ		Non-EJ	
Neighborhood	Sample Size	Sampling Error	Sample Size	Sampling Error
Arden	44	14.8%	-	-
South Natomas	81	10.9%	-	-
South Sacramento	319	5.5%	-	-
Del Paso Manor	-	-	298	5.7%
T Street	-	-	30	17.9%
Tahoe Park-Colonial Heights	-	-	128	8.7%
Total	444	4.7%	456	4.6%

Sampling error increases as sample size decreases. Therefore, the individual neighborhoods are associated with greater margin of error than the entire response set. It would take immense resources to achieve a large enough pool of respondents in each neighborhood to reduce error substantially. Higher sampling error does not invalidate statistically significant relationships between neighborhoods, it only makes them less likely to be detected. Consequently, neighborhood specific data is not reported on in this document unless a significant difference is detected at that level.

Meta Research (Meta) was contracted to conduct and report on this survey. Using a previous SMAQMD Check Before You Burn questionnaire as a draft[2], SMAQMD, STI and Meta staff designed this survey's questionnaire to address the study objectives. The questionnaire was programmed for a CATI (Computer Assisted Telephone Interviewing) system. Most of the questions were asked in a closed-ended format, while some were asked open-ended and responses were categorized for quantitative analysis. Interviews took approximately 8 minutes on average to administer. Respondents were screened for age (18+), ownership of a wood or pellet burning device, and to confirm residency in Sacramento County. Interviewing took place from December 2 through December 19, 2016 and from January 6 through January 22, 2017.

Unless otherwise noted, frequency percentages cited in this document represent adjusted frequencies, meaning that percentages have been adjusted to account for any non-responses (refusals to answer) or non-qualified responses (questions not answered due to answers to previous questions).

[2] Meta conducted the 2014 Check Before You Burn: Perceptions, Awareness, and Compliance Report.

Analysis and Reporting

All frequencies represent adjusted frequencies unless otherwise noted. Any 'don't know' or refusal was removed from calculations.

Because most items were measured using nominal or ordinal level data, Chi-Square statistics were employed frequently to determine if differences in responses exist between subpopulations. Other items that recorded interval or ratio level responses were tested using Analysis of Variance (ANOVA). Infrequently, specialized tests (such as Z-test and Fischer's Exact test) are used due to the sample sizes of subpopulations involved in an analysis. Each of these tests is used under different circumstances to determine if the variance in the distribution of responses to one survey item is significantly different between subpopulations within the sample (e.g. Community: EJ vs Non-EJ) such that it cannot be accounted for by chance alone. If this is the case, a significant difference is declared. This is explained further in the next section.

Statistical Significance

The level of significance for each test was set to a p value of less than .05, which equates to at least 95% assurance in the integrity of an identified significant relationship. That is, a significant relationship is one that cannot be accounted for by chance alone. Because the relationship cannot be accounted for by chance alone it is instead likely due to differences in the subpopulations being compared. It is assumed this relationship holds for members of the population who are not a part of the sample, but who share the quality being used to compare subpopulations. For example, it may be determined that a significant difference arises in the burning rates of EJ and Non-EJ communities such that Non-EJ respondents are more likely to burn in the evening. This means researchers are 95% sure that the difference in reported activity between EJ and Non-EJ respondents is due to their belonging to a particular community, and not to chance.

Caveat

The sole purpose of this report is to provide a collection, categorization and summary of public opinion data. Meta Research intends to neither endorse nor criticize the Check Before You Burn program, the Sacramento Metropolitan Air Quality Management District (SMAQMD), Sonoma Technology, Inc. (STI), Prosio Communications or their policies, products, or staff. The Client (SMAQMD) shall be solely responsible for any modifications, revisions, or further disclosure/distribution of this report.

Results and Conclusions

Device Ownership Highlights

- The most commonly owned device is an indoor fireplace, owned by 79% of all respondents.
- Device ownership rates are nearly synonymous between EJ and Non-EJ respondent groups. An indoor fireplace is the most frequently owned device by both groups.
- Respondents in the T Street (Non-EJ) neighborhood are less likely to own an indoor fireplace than those in the other neighborhoods (63% vs 79% avg.). Instead, these respondents are more likely to own outdoor wood burning fire pits (27% vs 15% avg.).
- EJ Community respondents are significantly less likely to own more than one device (6%) compared to Non-EJ Community respondents (10%).
- A small percentage of respondents in each neighborhood own more than one device and Del Paso Manor (Non-EJ) residents stand out as substantially more likely to own multiple devices (12% vs 8% avg.).

Overview

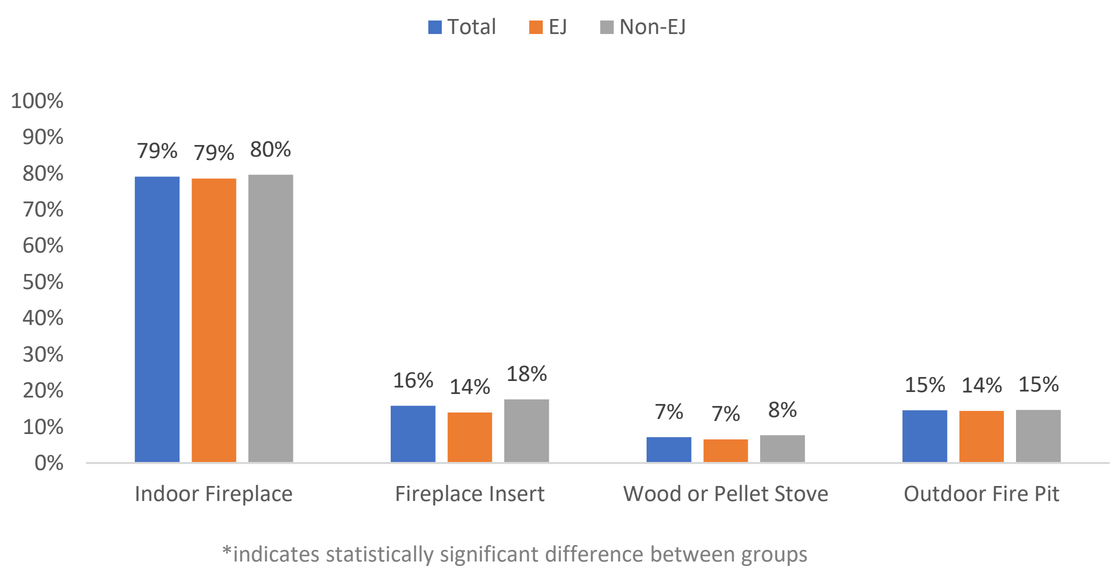
Few differences set device ownership within any neighborhood apart from the others, and no clear trends between EJ and Non-EJ communities offer extensive insight. In terms of neighborhood significant differences, Arden (EJ) residents are owners of *both* an indoor and outdoor device more often than the other five neighborhoods used in this study. Del Paso Manor (Non-EJ) residents are substantially more likely to own multiple indoor devices than each other neighborhood in the study. T Street (Non-EJ) residents exclusively own an outdoor fire pit more frequently than the others.

Overall, general ownership trends show indoor fireplaces as the most prevalent device. Ownership of the other devices is infrequent, variation between EJ and Non-EJ groups is nearly absent, and only slight variation is found between the neighborhoods. Because prevalence of devices other than indoor fireplaces is low among all neighborhoods, analyses of wood burning activity for those devices is tenuous.

Device Ownership Rates

The sample population included only Sacramento County residents from select EJ and Non-EJ communities who have the capability to burn wood, pellets, or manufactured logs using an indoor fireplace, fireplace insert, stove, outdoor fire pit, or chiminea. The most common device is an indoor fireplace, owned by 79% of all respondents. Ownership of fireplace inserts (16%), outdoor fire pits (15%) and stoves (7%) is much less prevalent.[3]

Figure 1: Device Ownership - Community
[All respondents]



Note: multi-response item; percentages will not add up to 100%

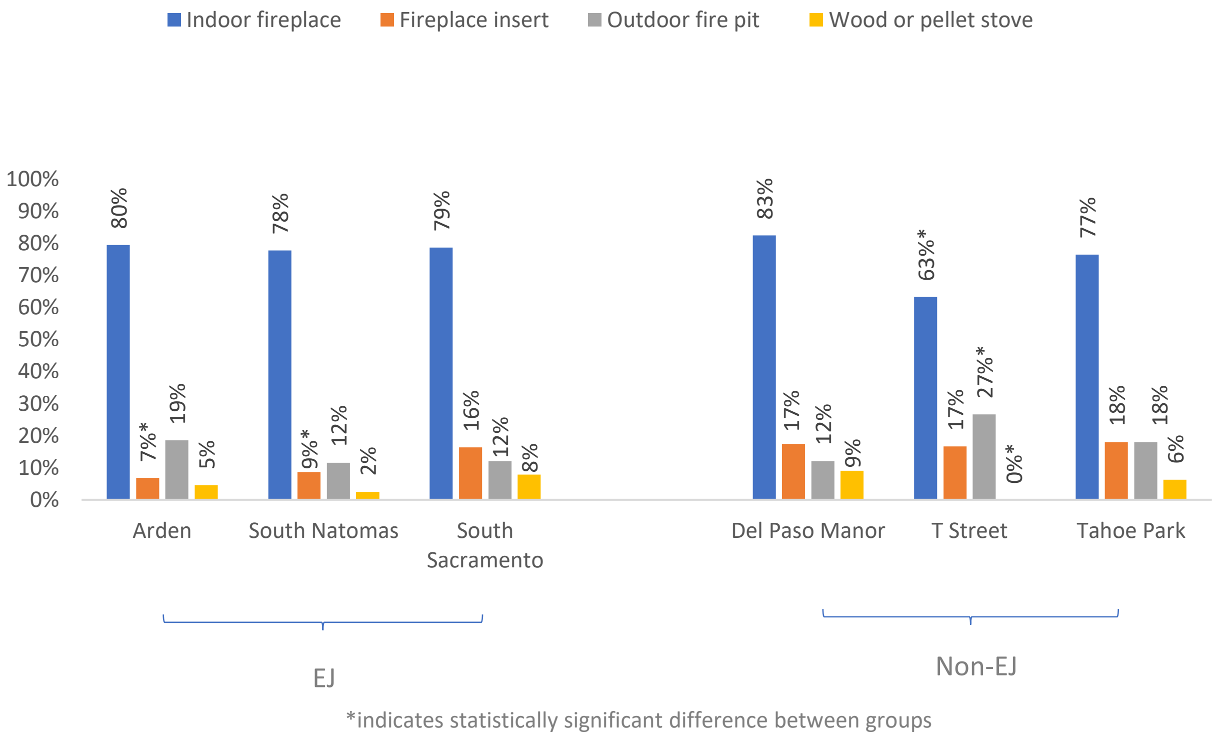
Device ownership rates are nearly synonymous between EJ and Non-EJ respondents. An indoor fireplace is the most frequently owned device by both groups. Chi-square analysis returned no significant relationship (p = 0.64) between community type and device ownership indicating that community alone is not enough to predict device type.

At the level of neighborhood, Chi-square analysis ($p < .05$) reveals significant differences between geographies. Respondents in the T Street $_{\text{(Non-EJ)}}$ neighborhood are less likely to own an indoor fireplace than those in the other neighborhoods (63% vs 79% avg.). Instead, these respondents are more likely to own outdoor wood burning fire pits (27% vs 15% avg.).

[3] Chiminea was removed from the analysis due to unreliable data. Rates of chiminea ownership were substantially greater in this study than they were in 2009 and 2014, suggesting miscommunication occurred and either respondents or interviewers were incorrectly stating chimney instead of chiminea.

In the Arden(EJ) and South Natomas(EJ) areas, respondents less commonly report owning fireplace inserts (7% Arden(EJ) and 9% South Natomas(EJ) vs 16% avg.). No respondents from T Street(Non-EJ) own wood stoves or pellet stoves.

Figure 2: Device Ownership - Neighborhood
[All respondents]



Note: multi-response item; percentages will not add up to 100%

Ownership: Device Views

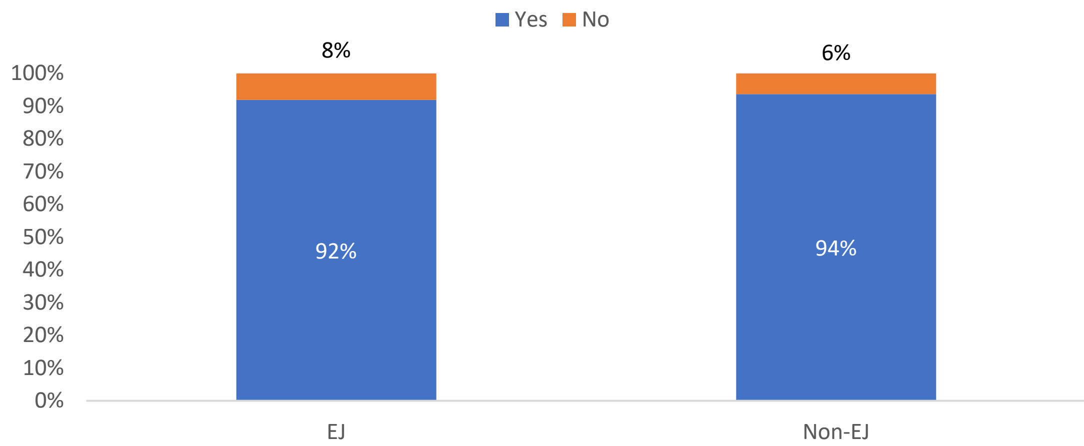
Beyond basic device ownership, respondents can also be split into a variety of different categories to aid understanding device ownership in each neighborhood:

1) those who own any indoor device;
2) those who own only an indoor fireplace or fireplace insert;
3) those who own more than one indoor device;
4) those who own only outdoor wood burning fire pits and;
5) those who own an indoor device and an outdoor fire pit.

Any Indoor Device

No significant differences distinguish EJ and Non-EJ communities for respondents owning any of the three major indoor devices (fireplace, fireplace insert, wood or pellet stove). Nearly all respondents report owning at least one of any indoor device.

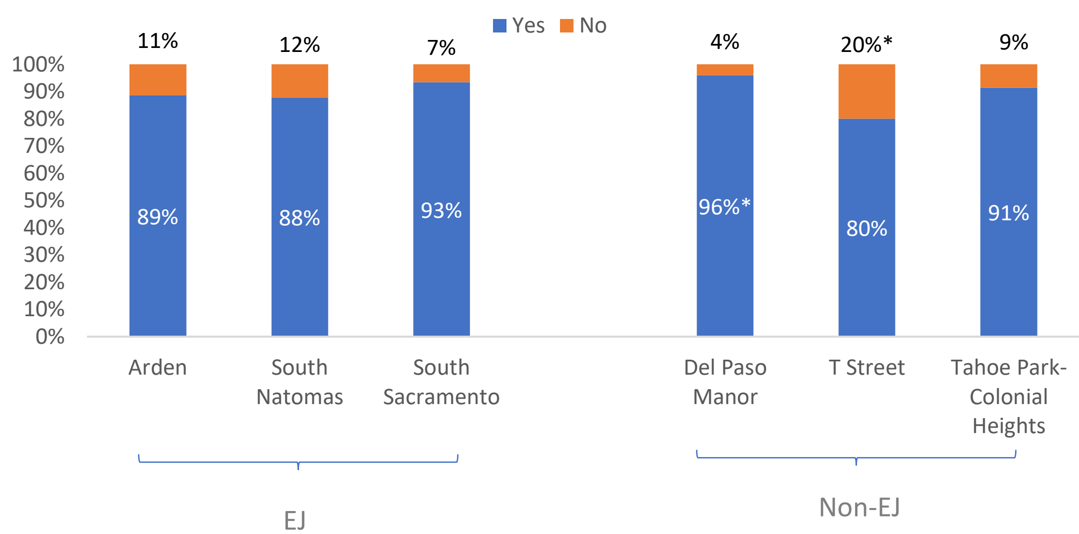
Figure 3: Device Ownership - Community: Any Indoor Device
[All respondents]



*indicates statistically significant difference between groups

At the level of neighborhood, Chi Square ($p < .01$) reveals Del Paso Manor (Non-EJ) residents are significantly more likely to own at least one of the three devices compared to the rest of the neighborhoods, while T Street (Non-EJ) residents are least likely to own one of the three.

Figure 4: Device Ownership - Neighborhood: Any Indoor Device
[All respondents]

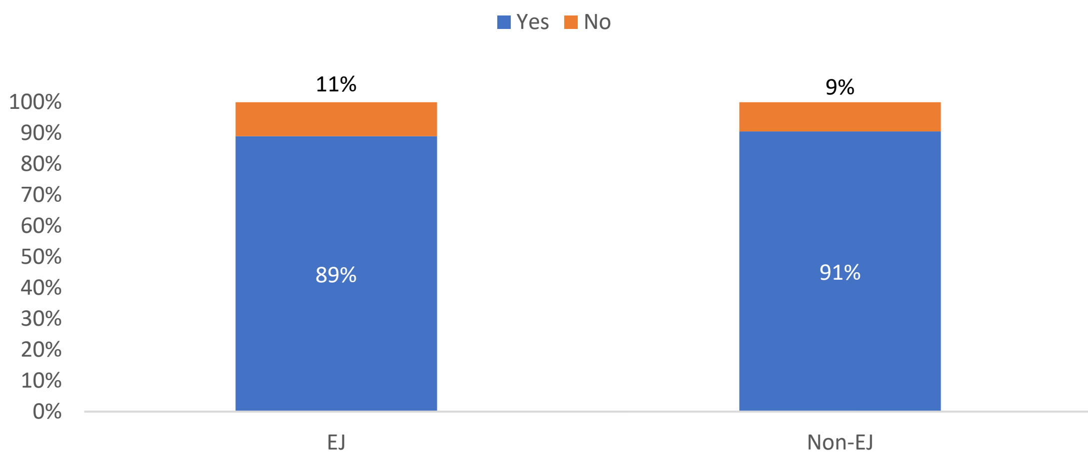


*indicates statistically significant difference between groups

Indoor Fireplace or Fireplace Insert

Since indoor fireplaces and fireplace inserts differ inherently from wood or pellet burning stoves in terms of emission production, ownership of one of these two devices warrants its own analysis. Yet this categorization of respondents at the community level reveals no significant relationships with a Chi Squared test ($p = 0.43$). In general, nine out of 10 respondents own either an indoor fireplace or fireplace insert.

Figure 5: Device Ownership by Community: Indoor Fireplace or Fireplace Insert [All respondents]

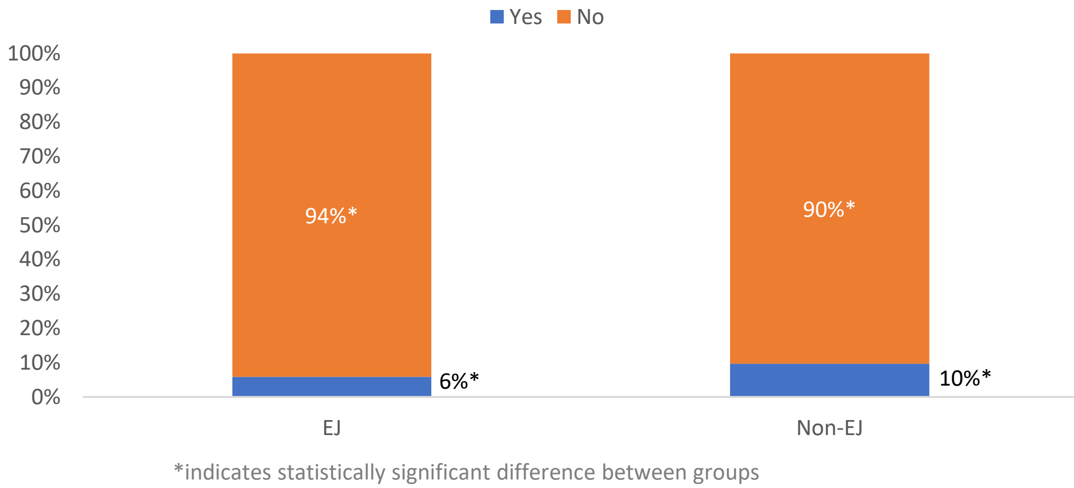


*indicates statistically significant difference between groups

More Than One Device

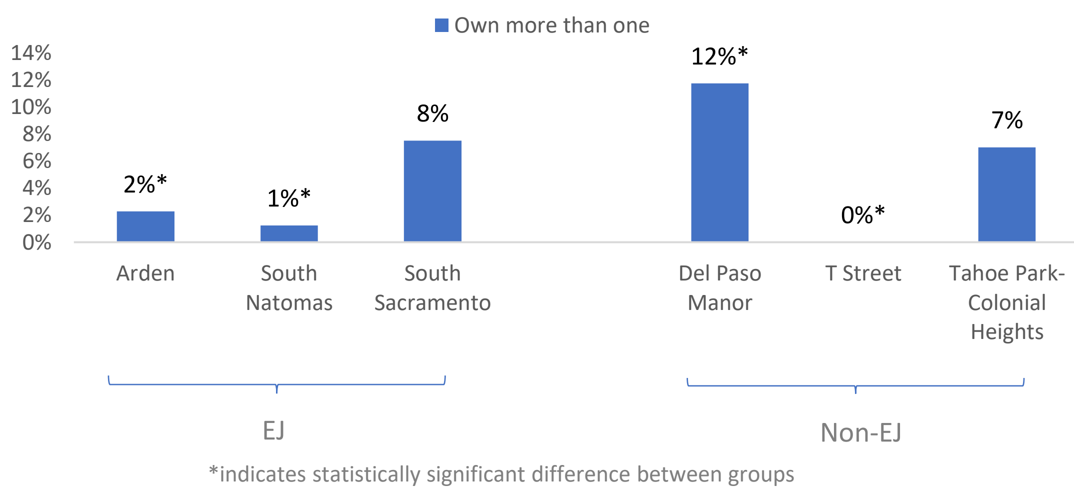
EJ and Non-EJ respondents in this study are not equally likely to own multiple devices. Chi Square ($p < 0.05$) reveals EJ respondents (6%) as less likely to own more than one device compared to Non-EJ respondents (10%). Still, respondents infrequently own more than one device.

Figure 6: Device Ownership - Community: More Than One Indoor Device [All respondents]



A small percentage of respondents in each neighborhood own more than one device. In this regard, Del Paso Manor (Non-EJ) residents are distinct from the rest. A significant Chi Square ($p < 0.005$) indicates that respondents from Del Paso Manor (Non-EJ) are substantially more likely to own multiple devices (12% vs 8% avg.). In contrast, Arden (EJ), South Natomas (EJ), and T Street (Non-EJ) respondents are least likely to own more than one of the three devices.

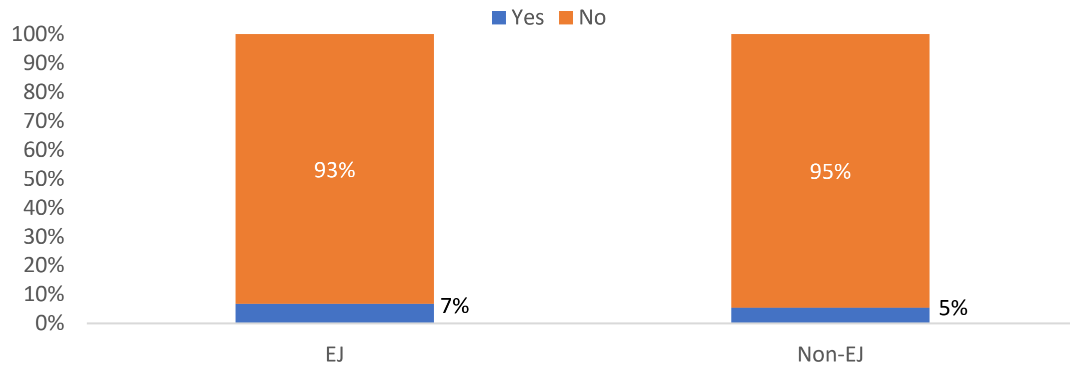
Figure 6 : Device Ownership - Neighborhood: More Than One Indoor Device [All respondents]



Only Outdoor

A select few respondents only own an outdoor fire pit, yet Chi Square ($p = 0.43$) finds no significant differences between EJ (7%) and Non-EJ (5%) respondents at the level of community.

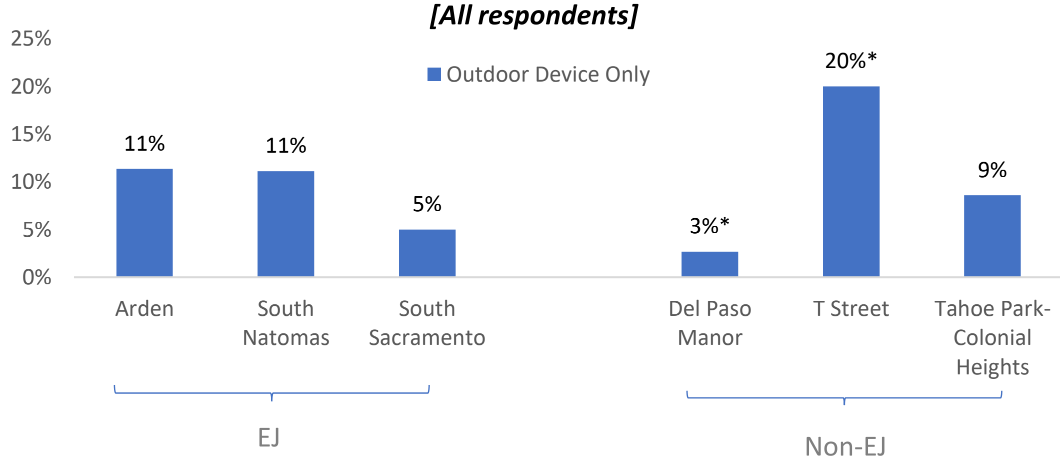
Figure 7: Device Ownership - Community: Only Outdoor Device [All respondents]



*indicates statistically significant difference between groups

Between neighborhoods, Del Paso Manor (Non-EJ) residents stand out again. Chi Square ($p < 0.005$) shows these respondents are least likely to own only an outdoor fire pit (3% vs 6% avg.). T Street (Non-EJ) residents are significantly more likely to own only an outdoor fire pit (20% vs 6% avg.) than the other neighborhoods.

Figure 8: Device Ownership - Neighborhood: Only Outdoor Device [All respondents]

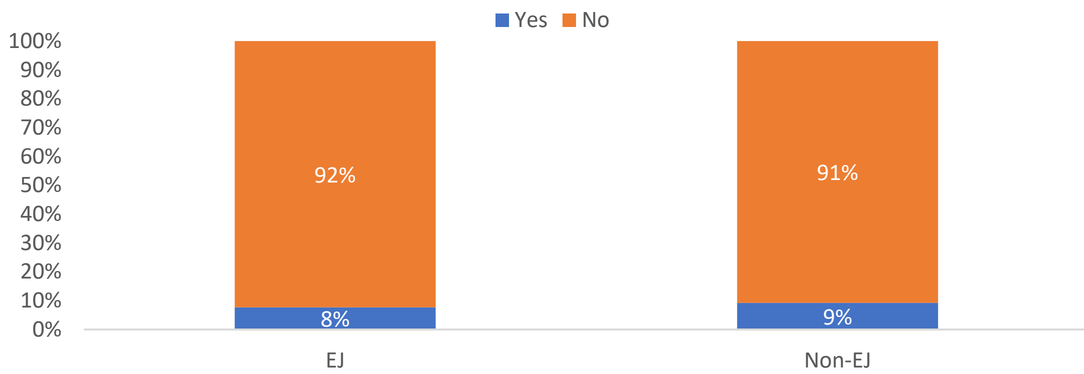


*indicates statistically significant difference between groups

Outdoor and Indoor

The final unique combination possible for device ownership is owning both an outdoor and an indoor device (indoor fireplace, fireplace insert, or wood or pellet stove). Few respondents from either community (8% EJ and 9% Non-EJ) own both an outdoor and indoor device. Chi Square reveals no significant relationship (p = 0.40)

Figure 9: Device Ownership by Community: Outdoor and Indoor Device [All respondents]



*indicates statistically significant difference between groups

Wood Burning Activity Highlights

- Respondents who burn with their device are doing so between one and two days per week. This frequency increases the more devices a respondent owns.

- Among all respondents, owners of wood or pellet stoves burn more frequently than owners of indoor fireplaces or fireplace inserts. The same is true when comparing the EJ and Non-EJ communities.

- Between EJ and Non-EJ communities, and including respondents who did not burn with their device at all, only use of indoor fireplaces results in a statistically significant difference in burning activity. Non-EJ community members more frequently use their indoor fireplaces (0.35 days per week) than EJ community members (0.23 days per week).[4]

- After removing respondents who did not burn with their device at all, indoor fireplace use becomes nearly equal between EJ and Non-EJ community members.

Overview

In general, respondents who burn with their device are doing so between one and two days per week. This frequency increases the more devices a respondent owns. Wood or pellet stoves are used most frequently out of the three indoor devices. Indoor fireplaces are used least frequently in all neighborhoods.

While significant differences between neighborhoods are nearly absent, some distinctions can be made at the community level. Of all respondents owning an indoor fireplace, the Non-EJ community is burning (0.35 days per week) significantly more than the EJ community (0.23 days per week).[4] Among respondents who burn with their fireplace inserts, those in Non-EJ communities are burning (1.83 days per week) significantly more often than respondents in EJ communities (1.20 days per week).[4]

Wood Burning Frequency

After defining which devices they own, respondents were asked a series of questions about how they used their device this winter for each of the three major devices owned (indoor fireplace, fireplace insert, and wood or pellet stove). The first of these questions asked respondents to estimate how frequently they burned with their device throughout

[4] See Figure 10 in the following section for definition of days-per-week calculation.

the winter months. This survey item is categorical[5], so estimating device use quantitatively requires assigning a frequency, in days, to each of six categorical options presented to respondents:

Figure 10: Burn Frequency Category Quantities	
Response Category	*Usage days*
a) Not at all	0
b) Only on Holidays	0.1
c) Less than once a week	0.5
d) About once a week	1
e) Mainly on Friday and Saturday nights	2
f) Two or more times a week	3

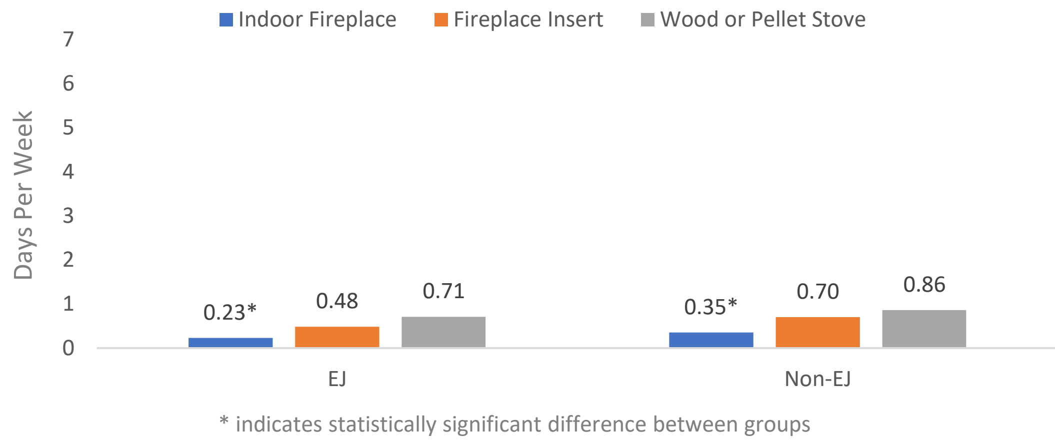
Using this scale, Figure 11 displays average device use in number of days per week for each device, separated by EJ and Non-EJ community type. Average frequency of use appears low using this scale because respondents report using their devices only occasionally. Most respondents claim to have never burned at all this winter.

Among all respondents, owners of wood or pellet stoves burn more frequently than owners of the other two devices. The same is true when comparing the EJ and Non-EJ communities. Wood or pellet stove use is greatest, followed by fireplace inserts, then indoor fireplaces. It's possible that these results are an artifact of ownership rates: because more respondents own an indoor fireplace, and most respondents did not burn at all this winter, indoor fireplace use will appear disproportionately infrequent compared to the others simply due to there being more non-burners within this group.

Though frequency of use appears to differ between EJ and Non-EJ respondents numerically, Analyses of Variance ($p < 0.05$) reveals that only use of indoor fireplaces results in a statistically significant difference. Non-EJ community members more frequently use their indoor fireplaces (0.35 days per week) than EJ community members (0.23 days per week).

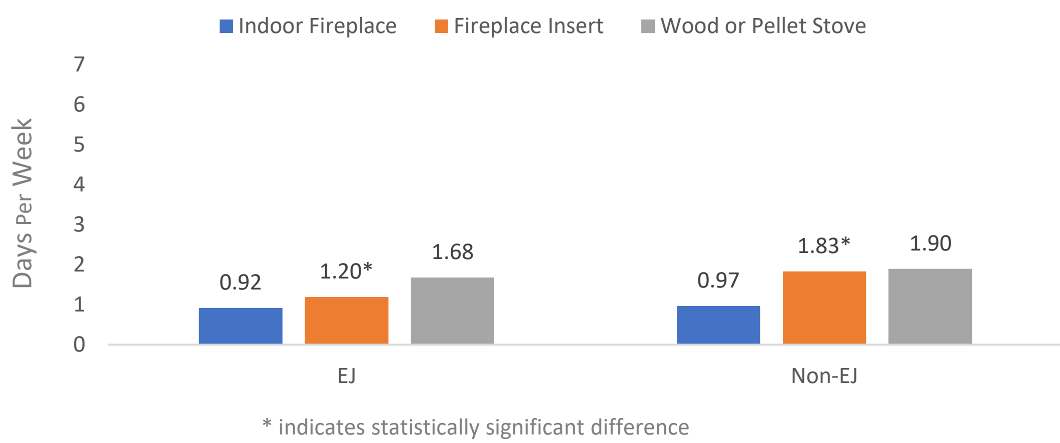
[5] This method of measurement was chosen to offer greater flexibility and detail in analysis, and to ensure a more accurate representation of behavior than a simple interval level questionnaire item asking only for a number of days per week of usage.

Figure 11: Device Usage by Community
[All device owning respondents]



By excluding respondents who report never using their device, indoor fireplace use becomes nearly equal between EJ and Non-EJ community members, but is still the least used device of the three. Instead, Analysis of Variance ($p < .05$) reveals a significant difference between EJ and Non-EJ fireplace insert users. Non-EJ respondents report burning more frequently with their fireplace inserts (1.83 days per week) than EJ respondents (1.2 Days per week).

Figure 12: Device Usage - Community
[Respondents who burn with their device]



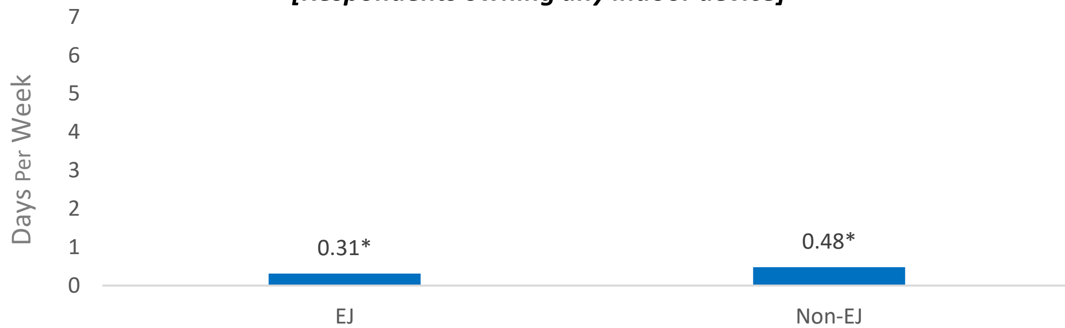
Wood Burning Activity: Device Views

To estimate relative device use among the views defined under the Ownership section of this report, usage per device was summed. That is, if a respondent owns more than one device then the reported use of those devices are summed to create a total usage per week value. For example, if a respondent owns both an indoor fireplace and a fireplace insert, and states they burned one day per week with each device, then they are considered to have burned two days per week (1 for indoor fireplace + 1 for fireplace insert = 2 total burn days).

Any Indoor Device

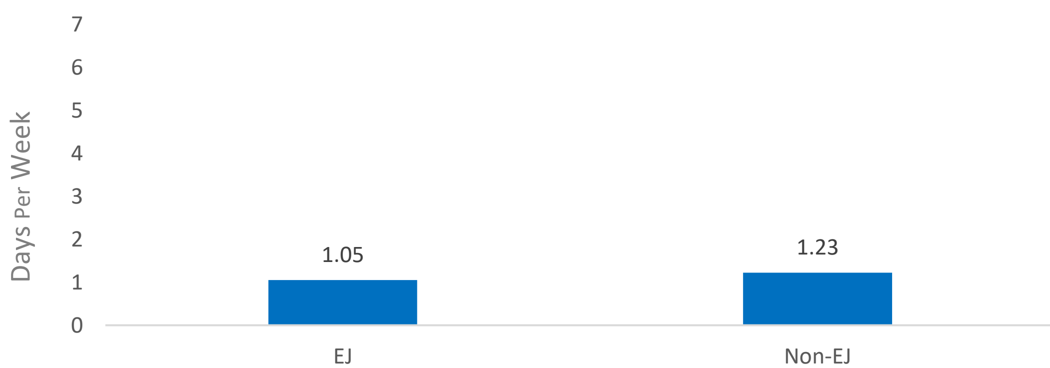
By viewing usage among respondents with any indoor device, a clear significant difference arises. A t-test ($p < 0.005$) shows EJ community respondents burn less frequently (0.31 days per week) than Non-EJ respondents (0.48 days per week).

Figure 13: Device Usage - Community: Any Indoor Device [Respondents owning any indoor device]



After removing those respondents who did not use their device this winter, while the relative frequency of burning increases, t-test ($p = 0.28$) reveals no significant differences between community. This means EJ and Non-EJ respondents are burning in similar frequency, among those who burn at all.

Figure 14: Device Usage - Community: Any Indoor Device [Respondents who burn with their indoor device]



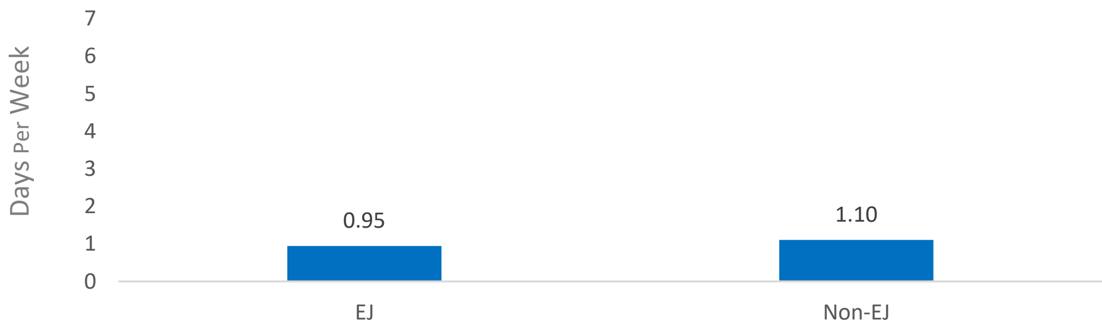
Indoor Fireplace or Fireplace Insert

Burning activity drops in general when measurement is excluded to indoor fireplaces and fireplace inserts only. This is expected as the device used to burn most frequently is the wood or pellet stove. A t-test ($p < 0.01$) exposes a significant relationship between community and burning frequency with an indoor fireplace or fireplace insert such that Non-EJ respondents are burning more frequently with their device than EJ respondents.

Figure 15: Device Usage - Community:
Fireplace or Fireplace Insert
[Respondents owning a fireplace or fireplace insert]

After restricting the view to include only respondents who burn with their indoor fireplace or fireplace insert, t-test finds no significant differences arise (p = 0.29). Respondents who burn with their fireplace or insert are burning approximately one day per week, regardless of community.

Figure 16: Device Usage - Community:
Fireplace or Fireplace Insert
[Respondents who burn with their fireplace or fireplace insert]



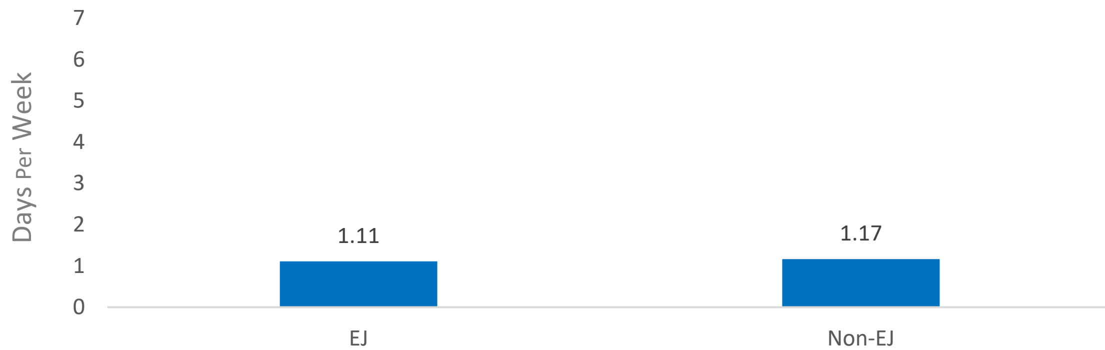
More Than One Device

The final device ownership recategorization that is applicable for wood burning activity analyses is that of respondents owning more than one indoor device. A very small percentage of respondents own more than one of the three major devices. No respondents from T Street report owning more than one device. Arden $_{(EJ)}$ and South Natomas $_{(EJ)}$ areas only include a single respondent owning more than one. From Tahoe Park-Colonial Heights $_{(Non\text{-}EJ)}$, nine respondents said they own more than one device.

The bulk of the data on burning frequency for multiple devices comes from South Sacramento (EJ) (24 multiple device owners) and Del Paso Manor (Non-EJ) respondents (35 multiple device owners).

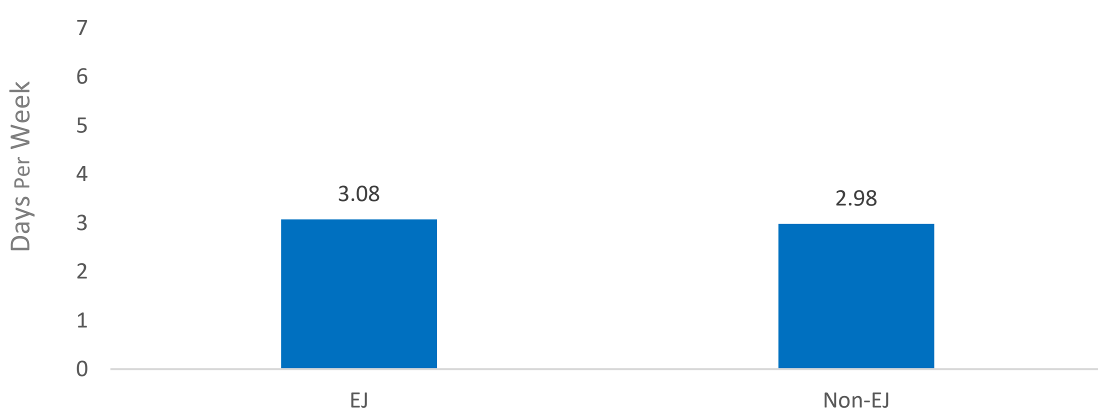
Compared to the other device ownership categories, multiple device owners burn the most frequently. A t-test (p = 0.91) uncovers no significant relationship between burning frequency with multiple devices and EJ or Non-EJ community.

Figure 17: Device Usage - Community: More than One Device [Respondents who own more than one indoor device]



Even among multiple device owners who burn, a t-test (p = 0.93) reveals no significant differences. Still, it is notable that frequency of burning for multiple device owning burners is nearly triple the rate of single device owning burners.

Figure 18: Device Usage - Community: More than One Device [respondents who burn more than one indoor device]



Specific Wood Burning Activity Highlights

- Regardless of device type, the majority of respondents did not burn at all this winter (67% indoor fireplace owners; 60% fireplace insert owners; 54% wood or pellet stove owners).

- Indoor fireplace owners in EJ communities burned significantly less frequently than their Non-EJ counterparts (72% EJ "not at all" vs 62% Non-EJ "not at all").

- Sample sizes within neighborhoods for fireplace insert and wood or pellet stove owners are small and impede detection of significant differences.

Overview

The following section depicts wood burning activity qualitatively, according to the categories offered while inquiring about respondent burning behavior with each of their three major devices.

As was confirmed in the quantitative depiction of wood burning behavior, with all three devices and across all neighborhoods, most respondents did not burn at all this winter. Of the respondents who did burn with their devices: those with indoor fireplaces mostly burned less than once per week or mainly on holidays. Those with fireplace inserts and wood or pellet stoves burned slightly more frequently, with most burning respondents saying they used their device between less than once per week, or two or more times per week.

Viewing the data by neighborhood, only indoor fireplaces offer a sample size substantial enough to securely make extrapolations. Among indoor fireplace owners, Arden $_{(EJ)}$, Del Paso Manor $_{(Non-EJ)}$ and T Street $_{(Non-EJ)}$ are each significantly more likely than the other three neighborhoods to use their device at all this winter. Arden $_{(EJ)}$ and Del Paso were most likely to burn with their indoor fireplace mainly on holidays than the other four while T Street $_{(Non-EJ)}$ respondents used their fireplace less than once per week.

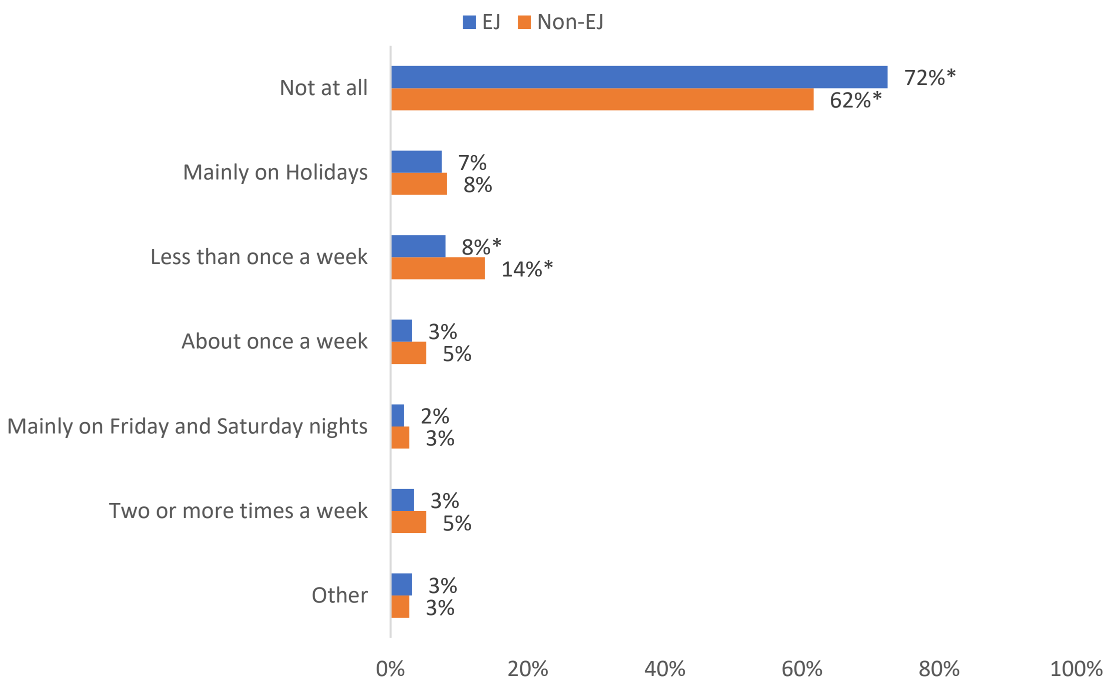
While there appear to be big differences in burning behavior between neighborhoods among fireplace insert and wood or pellet stove owners, they are not confirmed to be any more reliable than chance. For those devices, the overall EJ vs Non-EJ comparison serves as a safer platform of data from which to generalize.

Wood Burning Frequency

Indoor Fireplace

Of respondents who report owning an indoor fireplace, the majority did not use their device at all this winter (67%). Fireplace owners in EJ communities burned significantly less frequently than their Non-EJ counterparts (72% EJ "not at all" vs 62% Non-EJ "not at all")[6]. The respondents in the EJ community who are burning appear to be doing so less than once per week (8%) or mainly on holidays (7%). Non-EJ respondents are the same way. Most who are burning do so less than once per week (14%) or mainly on holidays (7%). The remaining indoor fireplace owners are burning more frequently.

Figure 19: Indoor Fireplace Use - EJ vs Non-EJ
[Respondents who own an indoor fireplace]

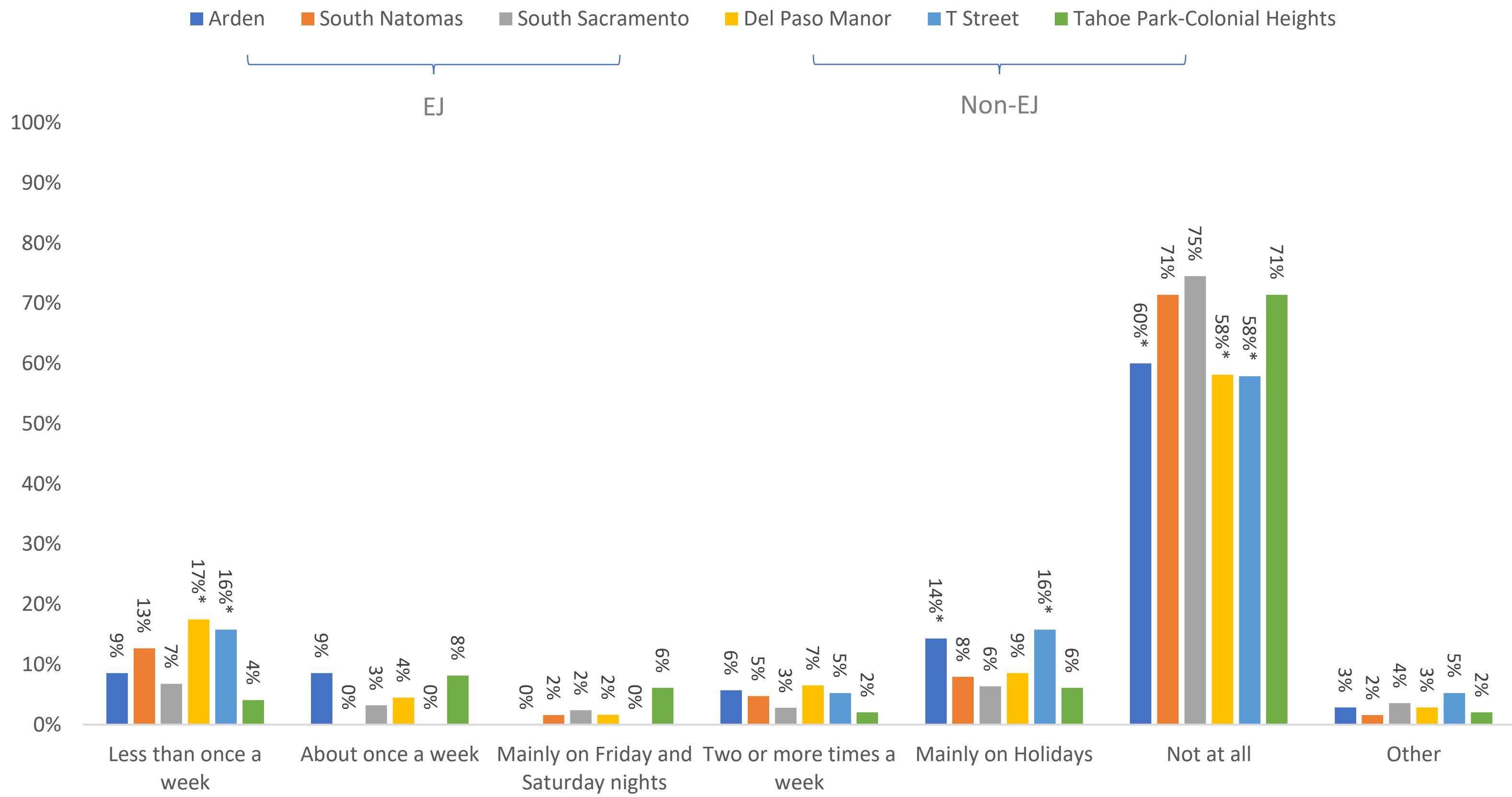


* indicates a statistically significant difference between groups

At the specificity of neighborhood, a Chi-Square analysis reveals significant differences ($p < 0.05$). Del Paso Manor $_{(Non-EJ)}$ and T Street $_{(Non-EJ)}$ neighborhoods are most likely to burn (42% burned with a fireplace vs 33% avg.). However, residents from these neighborhoods are most likely to say they burn less than once per week (17% and 16% respectively), suggesting that even though they are more likely to burn, they are burning infrequently. Likewise, residents in Arden $_{(EJ)}$ are more likely to burn (60% not at all), but only on holidays (14%). The same is true for T Street $_{(Non-EJ)}$ residents who burn. If they are not burning less than once per week, they are burning only on holidays (16%)

[6] $p < .05$

Figure 20: Indoor Fireplace Use: Neighborhoods
[Respondents who own an indoor fireplace]

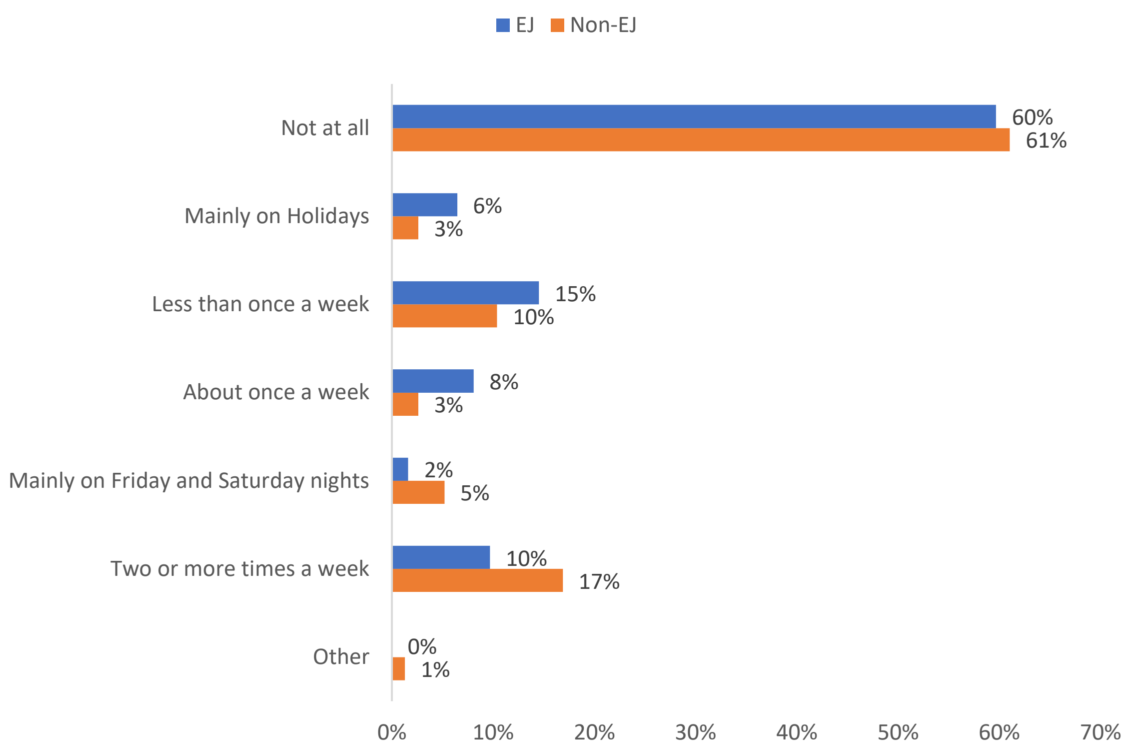


*indicates statistically significant difference between groups

Fireplace Insert

The Device Ownership and Wood Burning Activity sections established that fewer respondents own fireplace inserts, but those who do are burning more frequently than those with indoor fireplaces. Categorically, fireplace insert owners in both EJ and Non-EJ communities are mostly avoiding burning completely (60% and 59% "not at all," respectively). Those who do burn, are doing so less than once per week (15% EJ and 10% Non-EJ), or two or more times per week (10% EJ and 16% Non-EJ). According to a Chi Square (p = 0.22) no differences approached significance for EJ and Non-EJ fireplace insert owners.

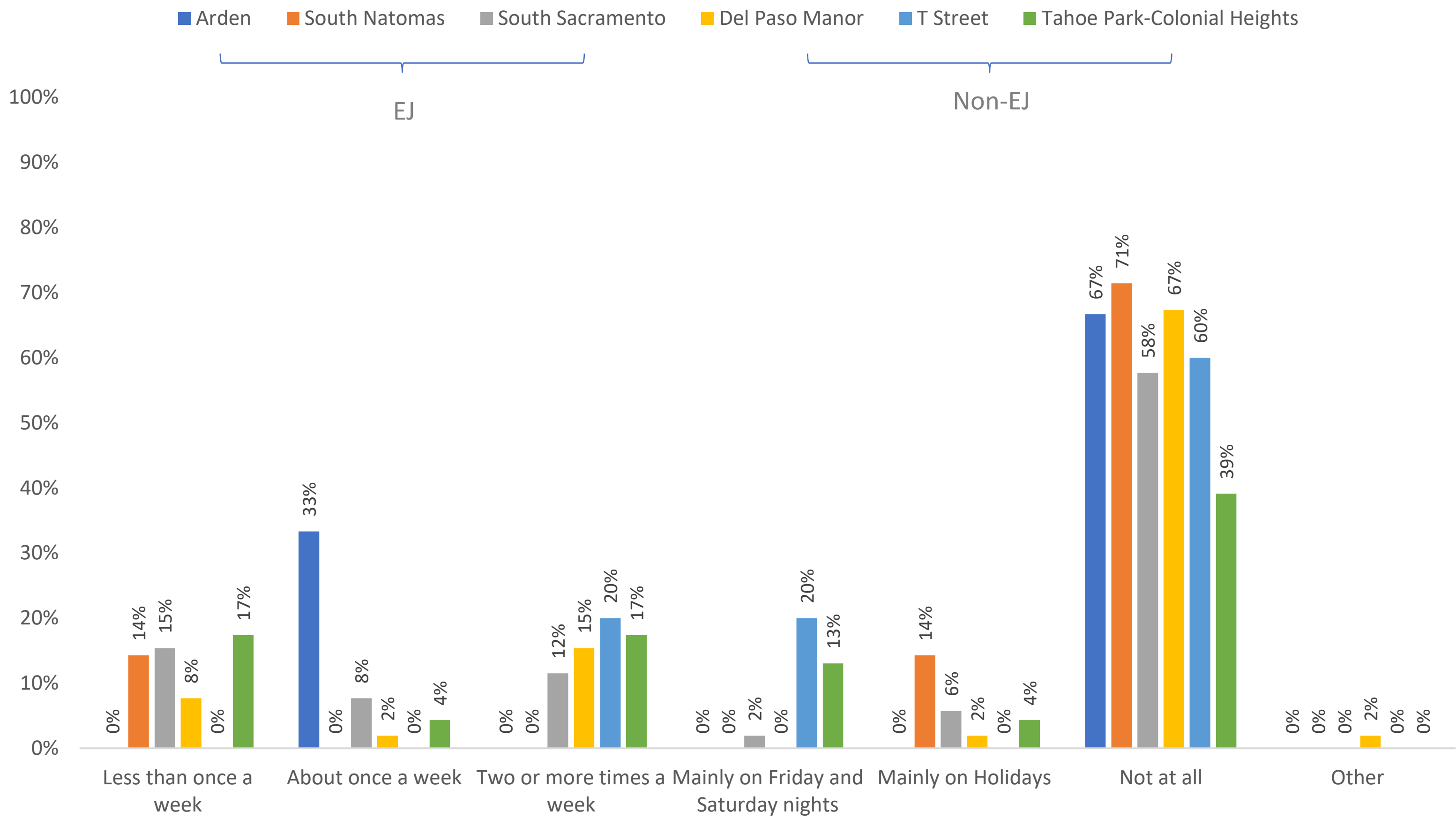
Figure 21: Fireplace Insert Use - EJ vs Non-EJ
[Respondents who own a fireplace insert]



* indicates a statistically significant difference between groups

While it appears fireplace insert use between neighborhoods varies wildly, a Chi Square (p = 0.50) test shows no relationship between geography and insert use.

Figure 22: Fireplace Insert Use: Neighborhoods
[Respondents who own an fireplace insert]

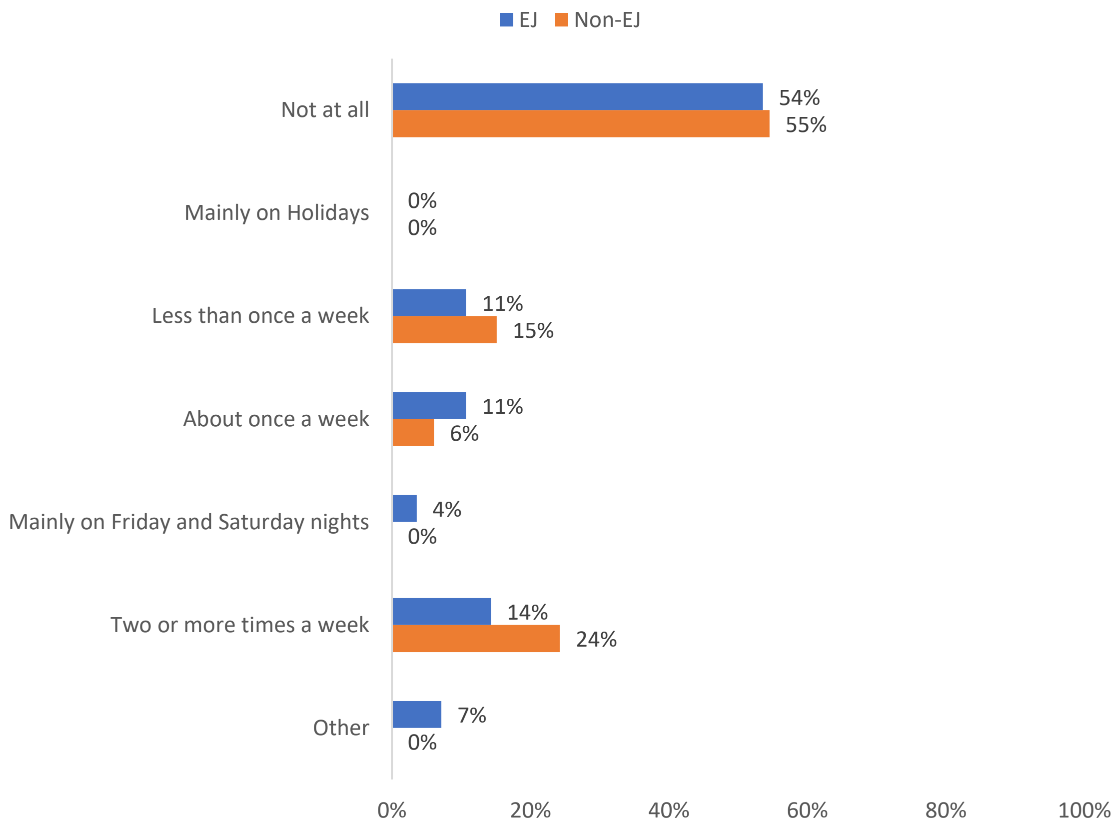


* indicates a statistically significant difference between groups

Wood or Pellet Stove

Among wood or pellet stove owners, a pattern similar to the other devices continues, and no significant differences arise between communities. Both EJ and Non-EJ respondents are most likely to say they didn't burn at all this winter (54% EJ and 55% Non-EJ). Non-EJ community members may be more likely than EJ to burn two or more times per week, but this marginal difference is not significant. From these data, the most reliable conclusion is that EJ and Non-EJ communities are equivalent in burning behavior with their wood or pellet stoves.

Figure 23: Wood or Pellet Stove Use - EJ vs Non-EJ [Respondents who own a stove]



* indicates a statistically significant difference between groups

Burn Periods Highlights

- Respondents who burn using an indoor fireplace are doing so mostly at night, regardless of community.

- The same is true for fireplace insert and wood or pellet stove owners: Most respondents are burning at night only for fireplace insert owners (76% EJ and 57% Non-EJ) and wood or pellet stove owners (10 of 13 EJ respondents; 9 of 15 Non-EJ respondents).

- With indoor fireplaces, Non-EJ respondents (79%) are more likely than EJ respondents (67%) to burn exclusively at night. Burning day *and* night is more likely among respondents in the EJ communities (19% EJ vs 9% Non-EJ).

- No significant differences distinguish one neighborhood from another for indoor fireplace burn periods.

- Sample sizes for neighborhoods among fireplace insert and wood or pellet stove owners are so small as to obstruct detection of significant differences and extrapolate to the overall neighborhood.

Overview

The quantitative burn frequency section indicated that EJ respondents burn less frequently than Non-EJ respondents with indoor fireplaces. The analysis on burn periods reveals more detail into that relationship. While, in days of the week, EJ respondents may burn with their fireplace less frequently than Non-EJ respondents, when they *do* burn, EJ respondents are more likely to burn day and night. Whereas Non-EJ respondents are more commonly burning only at night.

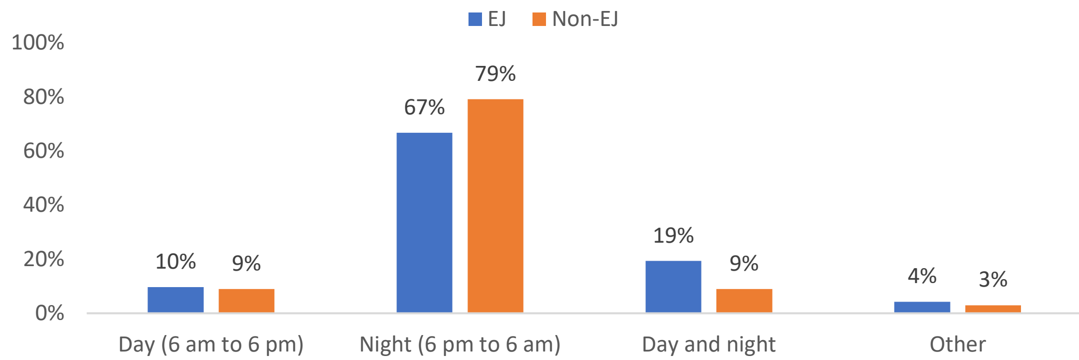
Similar results for fireplace inserts suggest the same kind of relationship, but statistically significant differences do not arise, meaning reported differences in burning behavior between EJ and Non-EJ respondents with fireplace inserts may be due to nothing more than chance. As for wood or pellet stoves, because of infrequent ownership, sample sizes of burners even at the level of community are too small to make generalizations. Instead, it is best to note that the data indicate the majority of wood or pellet stove burning respondents are using their stove at night only.

Device Burn Periods

Indoor Fireplace

Respondents who burn using an indoor fireplace are doing so mostly at night, regardless of community. However, Chi Square ($p < 0.05$) shows Non-EJ respondents (79%) are more likely than EJ respondents (67%) to burn exclusively at night. Burning day *and* night is more likely among respondents in the EJ communities (19% EJ vs 9% Non-EJ).

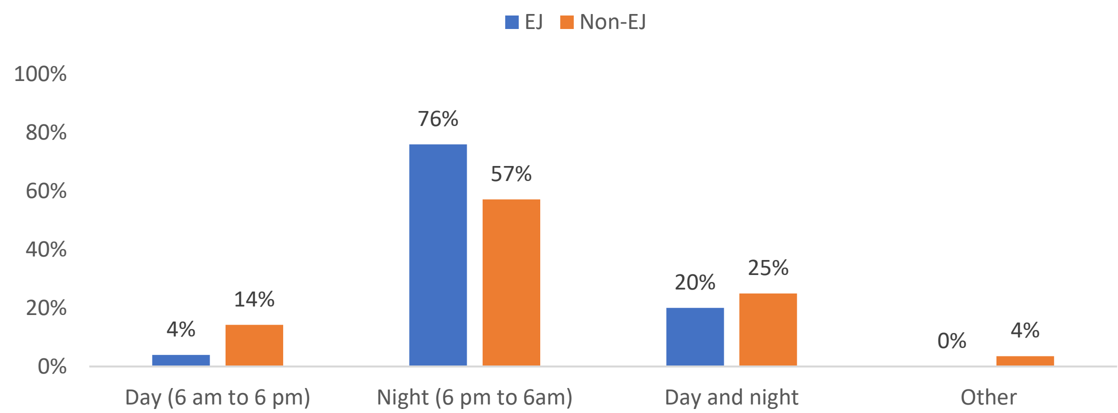
Figure 24: Indoor Fireplace Burn periods - EJ vs Non-EJ
[Respondents who burn with an indoor fireplace]
[Excludes "don't know" and "refused" responses]



Fireplace Insert

Fireplace insert burn periods reflect the same behavior as that found for indoor fireplaces. Most respondents are burning at night only (76% EJ and 57% Non-EJ). No significant relationships are found between EJ and Non-EJ communities. Overall, respondents who burn with fireplace inserts are doing so either at night exclusively, or both day and night. Few respondents burn mostly during the day only (4% EJ and 14% Non-EJ).

Figure 25: Fireplace Insert Burn periods - EJ vs Non-EJ
[Respondents who burn with an indoor fireplace]
[Excludes "don't know" and "refused" responses]

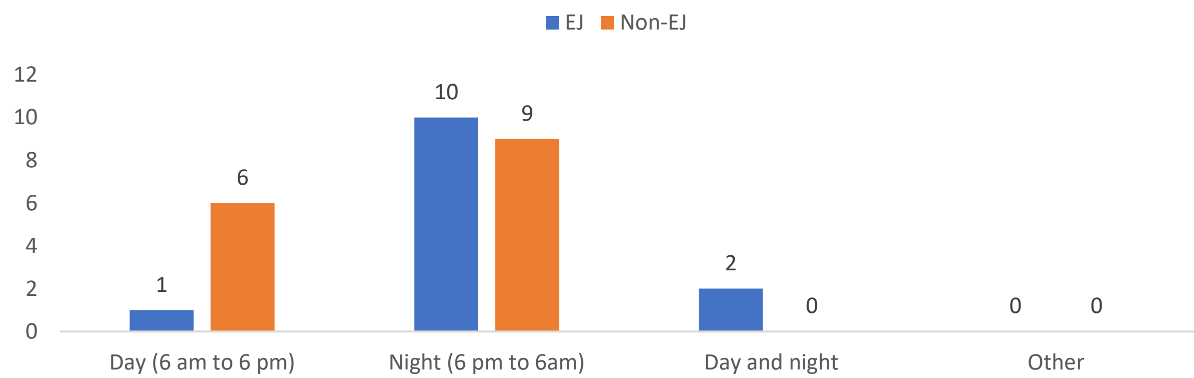


Wood or Pellet Stove

For wood or pellet stoves, results are also displayed as number of respondents instead of percentage values. Sample size is low, and displaying percentage values may be a distorted view of the data.

No significant differences are found between communities. Most EJ (10 of 13) and Non-EJ (9 of 15) burners using a wood or pellet stove are doing so at night exclusively. The other portion of Non-EJ burners are burning only during the day (6 of 15), while EJ burners are split between during the day (1 of 13) and both day and night (2 of 13).

Figure 26: Wood or Pellet Stove Burn periods - EJ vs Non-EJ
[Respondents who burn with an indoor fireplace]
[Excludes "don't know" and "refused" responses]
[Values in number of respondents]



The sample size for EJ and Non-EJ wood or pellet stove burners is almost entirely composed of South Sacramento $_{(EJ)}$ (10 of 13) and Del Paso Manor $_{(Non\text{-}EJ)}$ (13 of 15) respondents. Though each neighborhood is displayed below, caution is advised for any extrapolations beyond those from South Sacramento $_{(EJ)}$ and Del Paso Manor $_{(Non\text{-}EJ)}$. Even then, in the case of wood or pellet stove burners, results should not be considered securely representative of the neighborhood.[7]

[7] Sampling error at n = 10 and n = 13 is over +/- 25%. See methodology section for a note on the inordinate resources required to draw a secure sample size of this population.

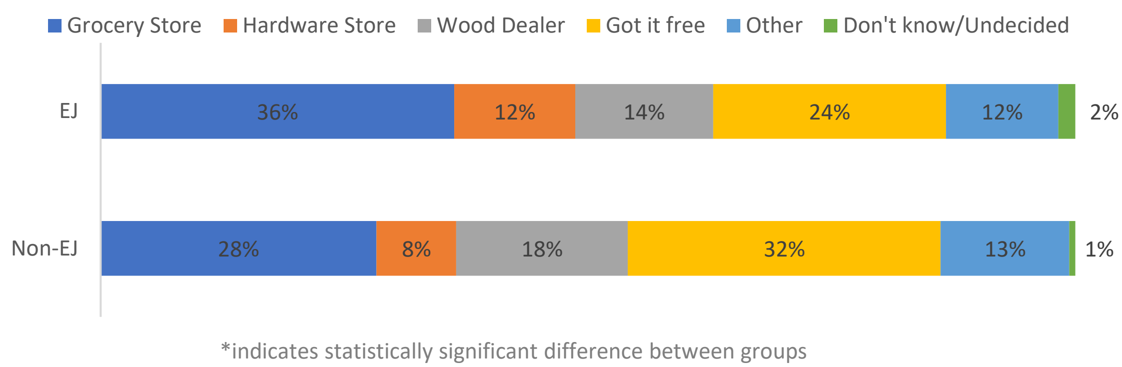
Wood Source

Any Indoor Device

The two most common methods of obtaining wood for both EJ and Non-EJ communities are grocery stores and getting it free. While Chi Square (p = 0.36) shows the marginal differences between the groups are not significant, in these data, EJ respondents who burn with any indoor device are most likely to purchase their wood from a grocery store (36%). Their Non-EJ counterparts are most likely to get theirs for free (32%).

At relatively similar rates, the two communities are finding wood at a wood dealer (14% EJ and 18% Non-EJ) or a hardware store (12% EJ and 8% Non-EJ). Approximately one eighth of all indoor burners - 12% EJ and 13% Non-EJ – are getting their wood from some source other than one listed. A small fraction is not sure where their wood came from.

Figure 27: Wood Source for Any Indoor Device - EJ vs Non-EJ
[respondents who burned with any indoor device]



U.S. Environmental Protection Agency (EPA) Certification Highlights

- A slight majority in both EJ (39%) and Non-EJ (39%) communities don't know if their device is certified.
- One third (34%) of EJ respondents say their indoor fireplace is certified, while just under one third (28%) of Non-EJ respondents report a certified device.
- For fireplace inserts, nearly half (48%) of EJ Respondents who burn with a fireplace insert report that their device is EPA certified. Just over half (53%) of their Non-EJ counterparts say theirs is too.
- Most respondents say that their wood or pellet stove is certified (62% EJ and 60% Non-EJ).
- No significant differences distinguish EJ and Non-EJ communities.

Overview

Once more, significant differences between respondent types are absent regarding knowledge of device EPA certification. Results confirm that often, respondents are unsure about their device certification. This is especially true for indoor fireplace owners. While sample sizes for fireplace insert and wood or pellet stove owners are tiny, the data do indicate that these respondents may more likely be certain their device is certified.

Overall, these data show that 34% of EJ and 28% of Non-EJ indoor fireplace owners are sure they are burning with an EPA certified fireplace while 27% EJ and 33% Non-EJ fireplace owners are sure that they are not. Indoor fireplaces are the most commonly owned devices by far, but are used for burning less frequently than the other two devices.

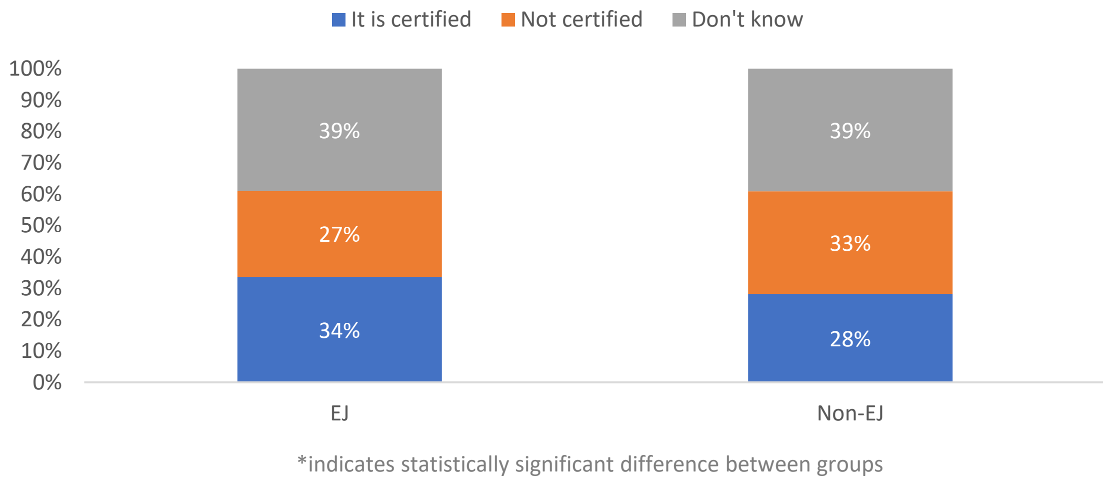
Respondents seem more likely to know that the device they use to burn is EPA certified if it is a fireplace insert or wood or pellet stove, though statistical comparisons between device owners did not turn up significant differences.

Device Certification

Indoor Fireplace

Respondents who used their device this winter were asked if it is EPA certified. Responses are split nearly in thirds among residents who burn with an indoor fireplace. The slight majority in both EJ (39%) and Non-EJ (39%) communities don't know if their device is certified. One third (34%) of EJ respondents say their device is certified, while just under one third (28%) of Non-EJ respondents report a certified device. The others, 27% EJ and 33% Non-EJ, report not owning an EPA certified device. Chi Square (p = 0.59) finds no significant differences distinguish the slight variations in percentages of EJ and Non-EJ community members.

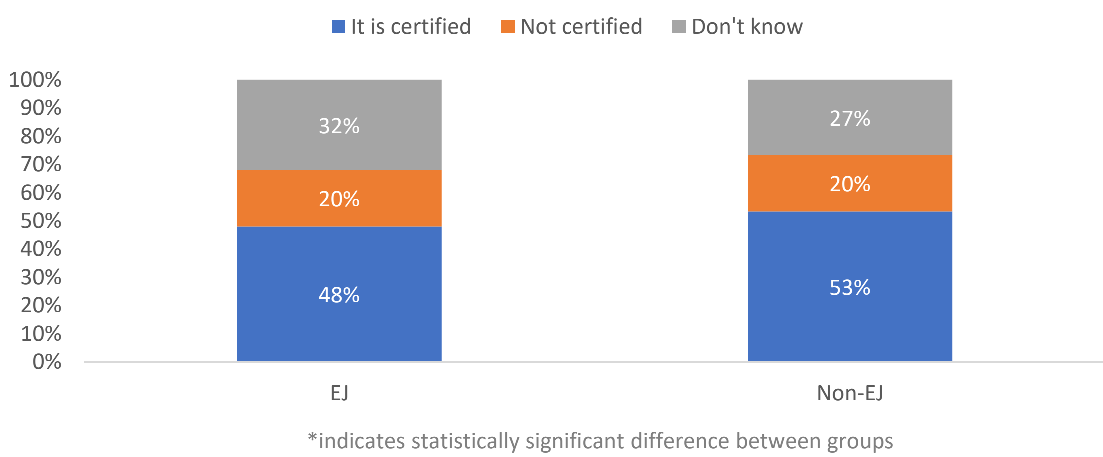
Figure 28: Indoor Fireplace EPA Certification - EJ vs Non-EJ
[Respondents who burn with their indoor fireplace]



Fireplace Insert

For fireplace insert owners, there is more certainty regarding device certification. Nearly half (48%) of EJ Respondents who burn with a fireplace insert report that their device is EPA certified. Just over half (53%) of their Non-EJ counterparts say theirs is too. However, one third of EJ insert burners (32%) are unsure about their device, and over a quarter (27%) of Non-EJ insert burners are unsure of theirs. EJ and Non-EJ respondents appear equally likely to burn with an uncertified fireplace insert (20% each). No significant differences arise between respondent types according to a Chi Square (p = 0.90).

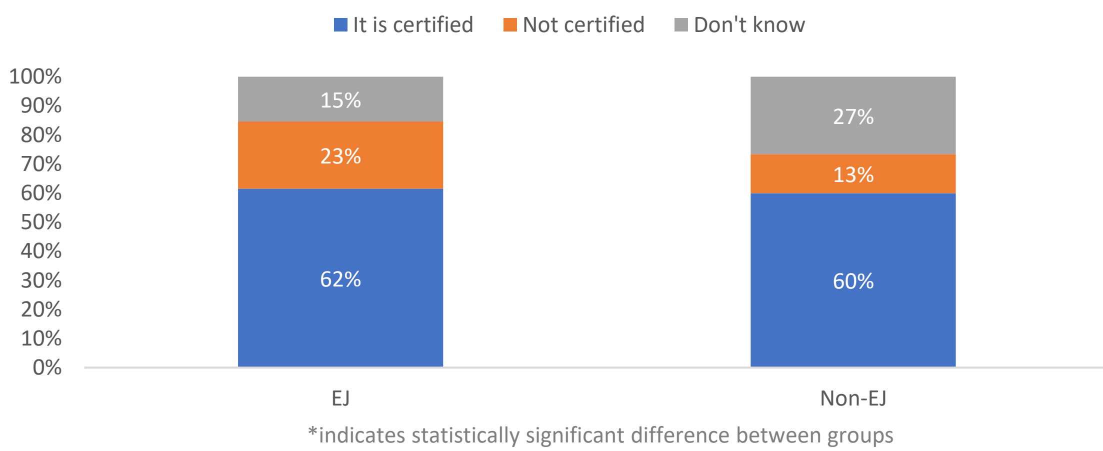
Figure 29: Fireplace Insert EPA Certification - EJ vs Non-EJ
[Respondents who burn with their fireplace insert]



Wood or Pellet Stove

Ownership of wood or pellet stoves is the least common of the three major devices, which means sampling error when evaluating wood or pellet stove burners is high and results should be interpreted with care. Keeping caution in consideration, knowledge of EPA device certification is not significantly different between EJ and Non-EJ respondents. Most respondents say that their wood or pellet stove is certified (62% EJ and 60% Non-EJ). This proportion of certification is the greatest of the three major devices, though Chi Square (p = 0.68) comparing the groups does not reach significance.

Figure 30: Wood or Pellet Stove EPA Certification - EJ vs Non-EJ [Respondents who burn with their wood or pellet stove]



"Check Before You Burn" Program Awareness & Compliance Highlights

- Unaided awareness (i.e. no prompt) is at 49% among all respondents. This percentage increases to 85% after aided awareness (i.e. after description).[8]
- In terms of unaided awareness:
  - EJ respondents are less likely to be aware than Non-EJ respondents (45% EJ vs 52% Non-EJ).
  - Arden $_{(EJ)}$ neighborhood residents (61%) are more likely to be aware than the other two EJ neighborhoods (44% each).
  - Non-EJ respondents are substantially more likely than EJ respondents to cite the newspaper and/or radio as the source of their information.
  - EJ respondents are more likely to cite television as their information source.
- Combining unaided and aided awareness, 85% of respondents are familiar with the program.
- Burners reduce their burning because of notices not to burn approximately half the time (49%)
- EJ and Non-EJ burning respondents do not differ in their compliance rates.

Overview

In total, Check Before You Burn awareness levels are high, with 85% of respondents saying they are aware of information about reducing burning because of poor air quality. Nearly half of respondents (49%) said they were aware of this information without any aiding. A further 36% recognized the program after a brief description. In terms of unaided awareness, EJ respondents (45%) significantly were less likely to say they were familiar with burning reduction information than Non-EJ respondents (52%). Yet in total, there are no significant differences distinguishing the EJ community (83% total aware) from the Non-EJ community (87% total aware).

Just under half of respondents (46%) who burned with their device this winter say they reduced the number of fires they burned because of notices not to burn. Compliance rates based on survey responses within the selected EJ (46%) and Non-EJ communities (47%) are nearly synonymous.

Unaided Awareness

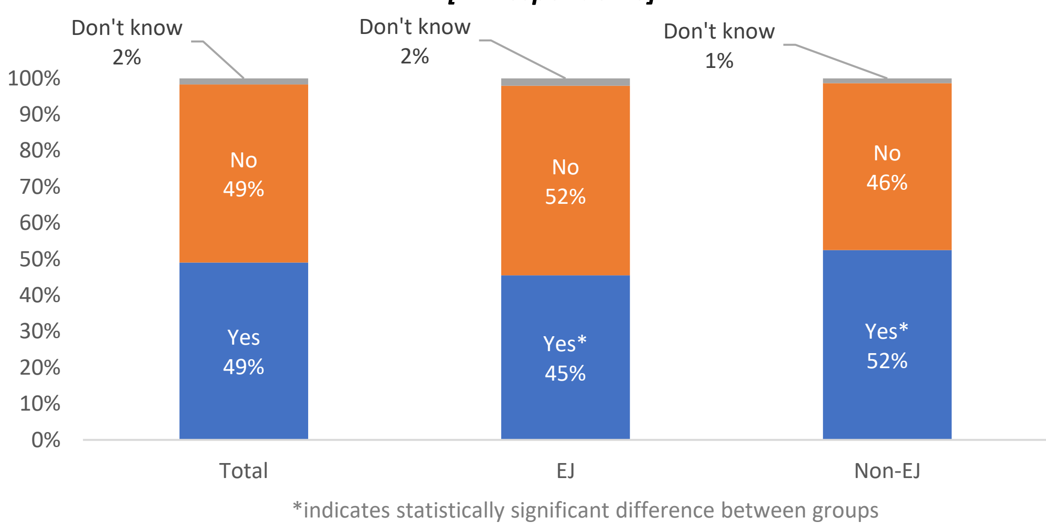
After the burning behavior survey questions, respondents were asked about their awareness of the Check Before You Burn program that was in effect at the time of this survey. Specifically, each respondent was asked:

[8] Note that aiding awareness does not diminish the legitimacy of an awareness measure. In fact, it is necessary to include in an overall awareness figure to account the varying levels of immediacy with which respondents can recall brands and messaging.

This winter, did you hear, read, or see anything informing residents not to use their wood burning fireplaces or outdoor fire pits because of poor air quality?

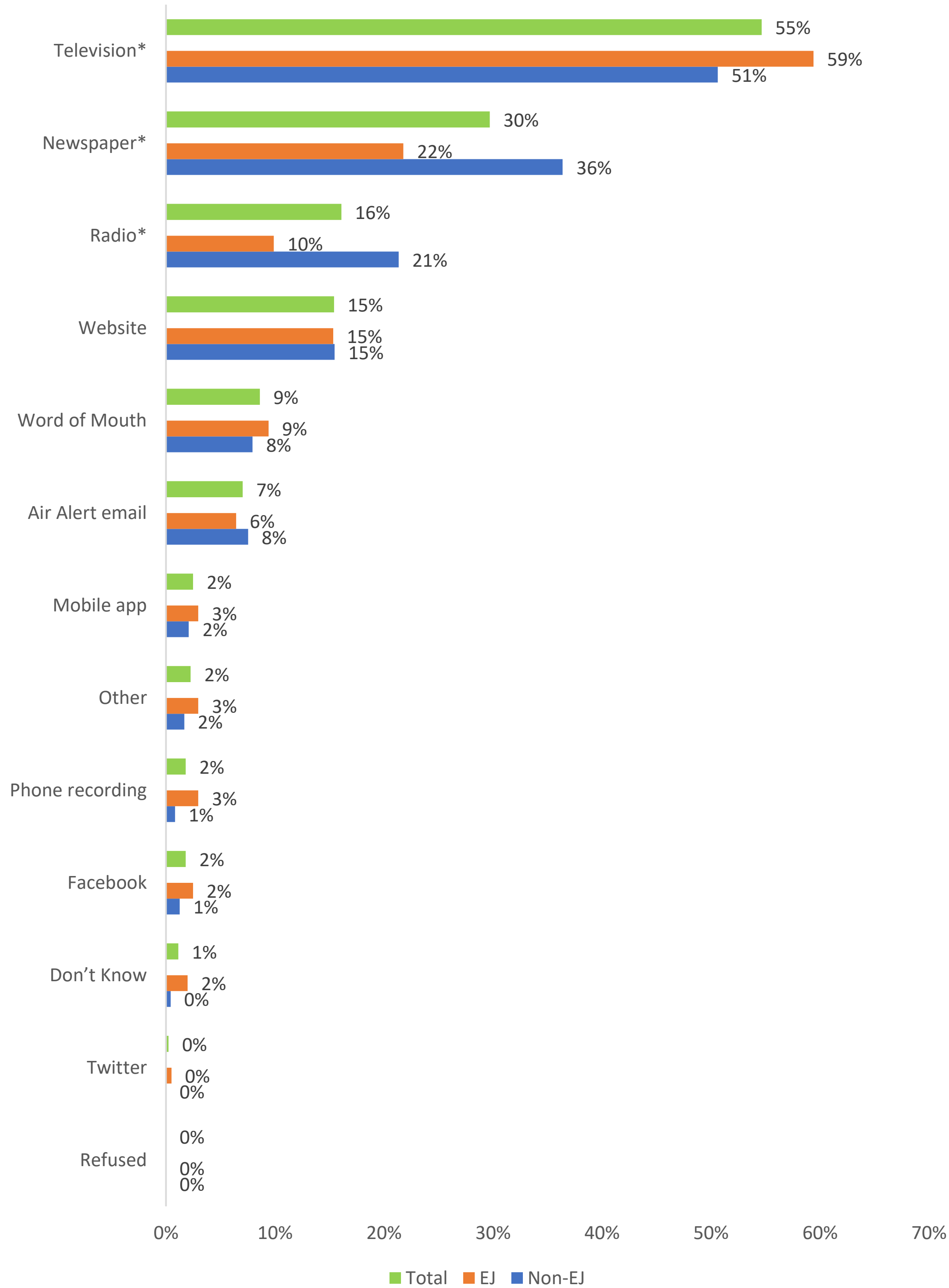
In total, 49% of respondents said they had seen or heard the information, but Chi Square shows the communities reported significantly different awareness levels. A total of 45% of the EJ respondents, compared to 52% of Non-EJ respondents, said they were aware of the information on wood burning and poor air quality.

Figure 31: Unaided Awareness - EJ vs Non-EJ [All respondents]



Why this difference exists may be found within respondent stated sources of information. A Chi Square ($p < 0.005$) test reveals that EJ respondents are significantly more likely to say they heard about wood burning and air quality from television (59% EJ vs 51% Non-EJ), while the Non-EJ respondents are more likely to say they saw it in the newspaper (36% Non-EJ vs 22% EJ), or radio (21% Non-EJ vs 10% EJ). Moreover, the Non-EJ respondents stated more sources of information overall, indicating that they received it from more than one source more commonly than EJ respondents. Exposure to information on multiple occasions through multiple sources may improve recall and increase unaided awareness.

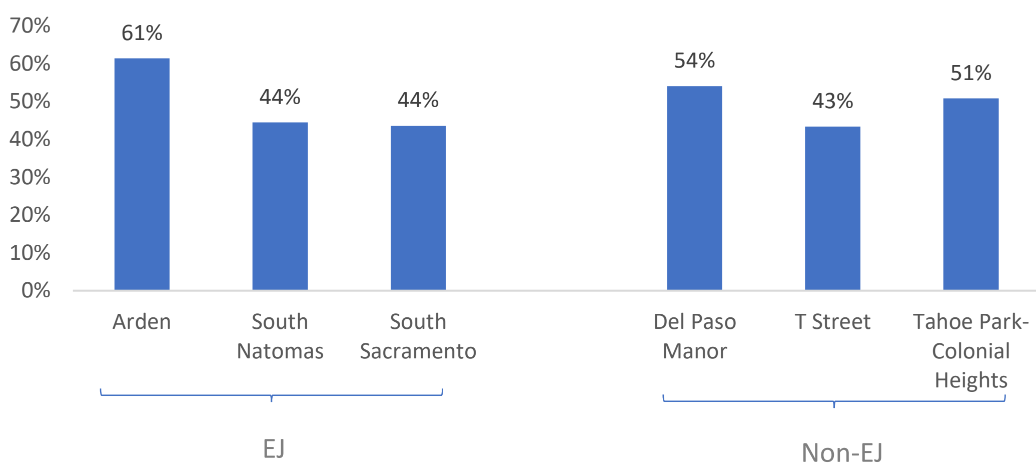
Figure 32: Sources of Check Before You Burn Information - EJ vs Non-EJ [All respondents]



For the surveyed EJ communities, 61% of Arden (EJ) respondents said they had read, seen, or heard information about wood burning and poor air quality. However, the other two, South Natomas (EJ) and South Sacramento (EJ), each had only 44% awareness (unaided), which brings the overall awareness total down.

For the surveyed Non-EJ communities, Del Paso Manor (Non-EJ) (54% aware) and Tahoe Park-Colonial Heights (Non-EJ) (51% aware) contribute to the higher awareness of the Non-EJ community. Whereas T Street (Non-EJ) respondents, at 43% aware, are similar to South Natomas (EJ) and South Sacramento (EJ).

Figure 33: Unaided Awareness - Neighborhood [All respondents]

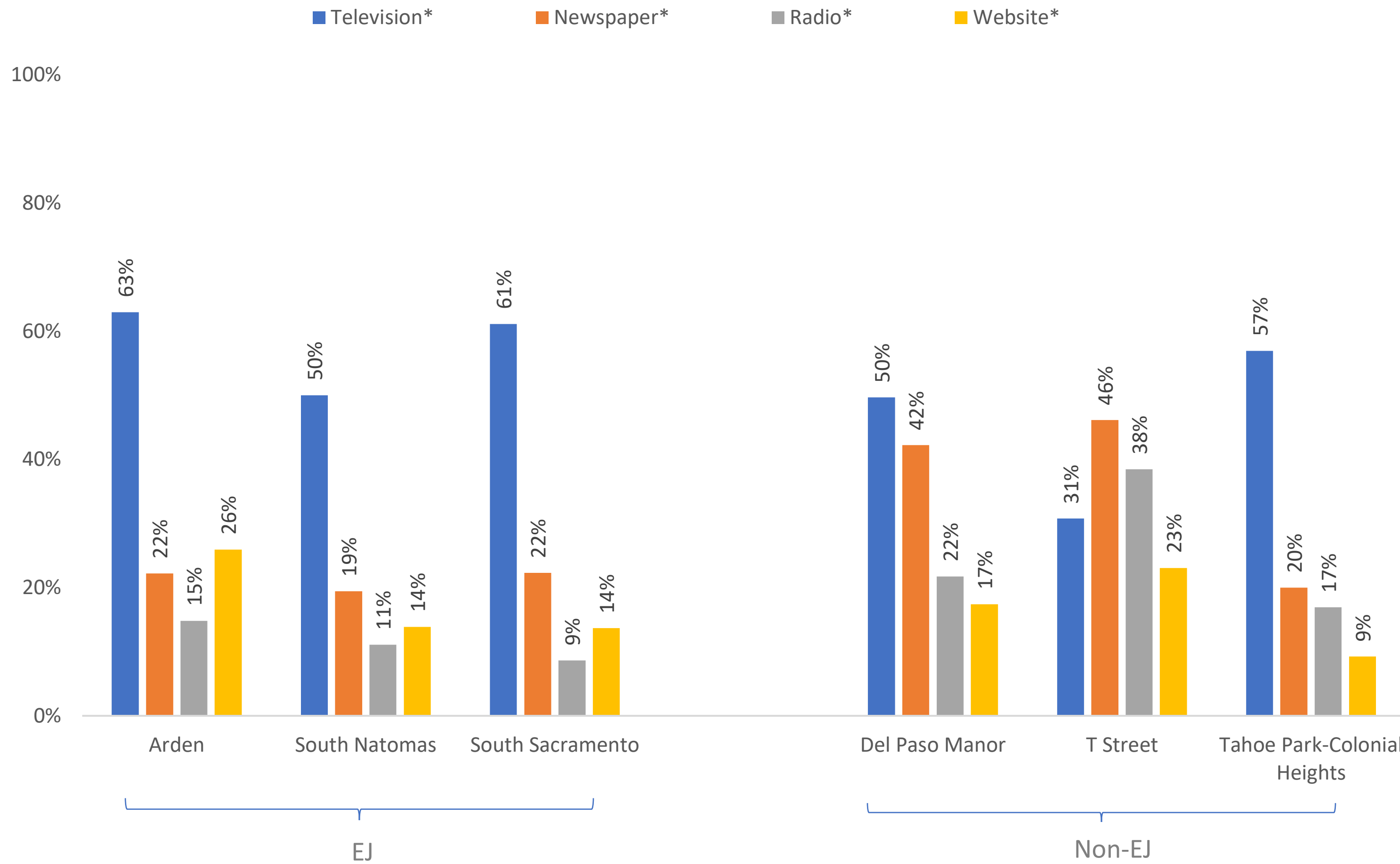


*indicates statistically significant difference between groups

Significant differences arise between neighborhoods in terms of the sources of their information, indicated by a Chi Square ($p < 0.05$). Arden (EJ) (63%), South Sacramento (EJ) (61%) and Tahoe Park-Colonial Heights (Non-EJ) (57%) are the most common citers of television as their information source. T Street (Non-EJ) respondents appear distinct in this regard as only 31% said they saw information on television.

Newspaper as an information source was referenced more often by the Non-EJ community, but at the neighborhood level it becomes clear that Del Paso Manor (Non-EJ) (42%) and T Street (Non-EJ) (46%) residents are unique in their common use of the newspaper as a source of information. Similarly, these two neighborhoods are most likely to have heard information on the radio. Finally, Tahoe Park-Colonial Heights (Non-EJ) residents stand alone as least likely to cite the website as their information source (9%).

Figure 34: Sources of Check Before You Burn Information - Neighborhood [All respondents]



*indicates statistically significant difference between groups

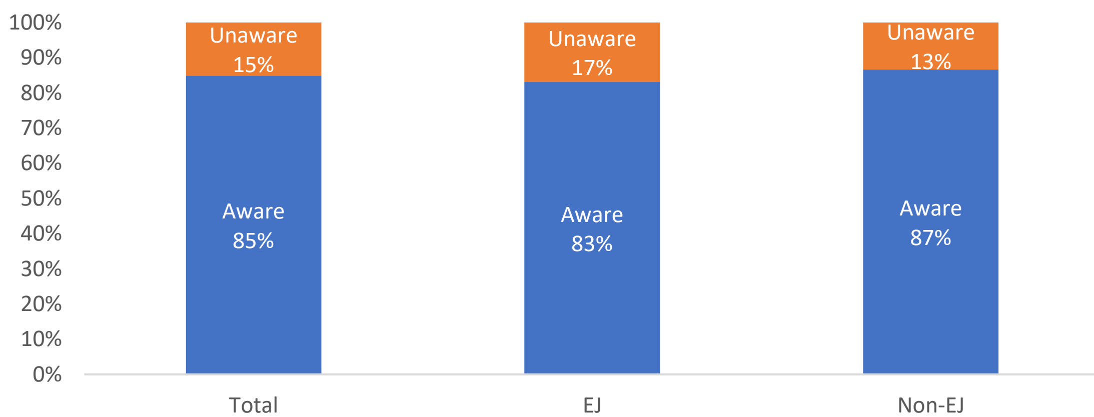
Aided Awareness

If a respondent did not answer "Yes" to the unaided awareness question, they were presented with a follow up question that described the Check Before You Burn program:

> *You may or may not have heard that in Sacramento County, it's the law that from November through February residents and businesses are prohibited from using indoor or outdoor fireplaces, wood stoves, and fire pits that burn wood, pellets, manufactured logs or any other solid fuel on days when air quality is forecast to be unhealthy to breathe. It is your responsibility to Check Before You Burn, to see if it is permissible to light a fire.*
>
> *Does this now sound familiar to you?*

Combining the percent aware from the unaided measure and the percent aware from the aided measure, total awareness of the Check Before You Burn program is at 85% for these communities. Chi Square (p = 0.14) finds no statistically significant differences distinguish the EJ communities from the Non-EJ communities

Figure 35: Total Awareness - EJ vs Non-EJ [All respondents]

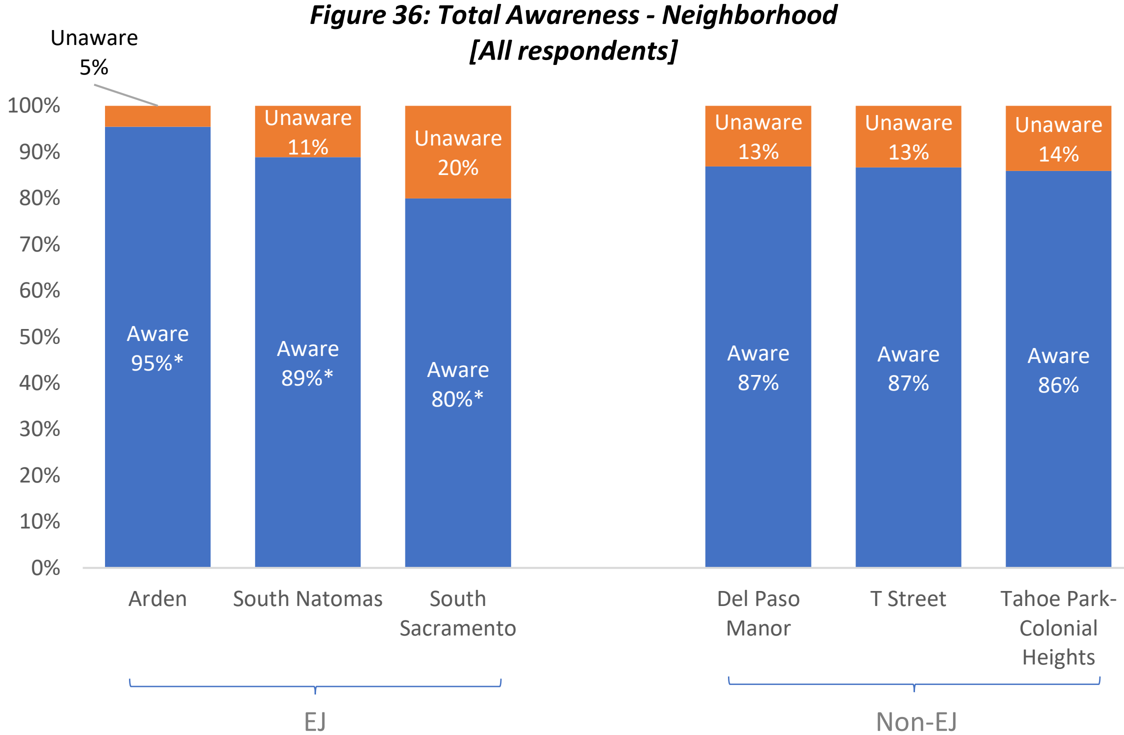


*indicates statistically significant difference between groups

The image sharpens slightly when using the lens of neighborhood. The Non-EJ neighborhoods are all nearly equal in total awareness rates. Chi Square ($p < 0.05$) reveals the EJ neighborhoods, on the other hand, vary significantly. Arden $_{(EJ)}$ residents are most likely to be aware of the program overall (95%), followed by South Natomas $_{(EJ)}$ (89%), and then South Sacramento $_{(EJ)}$ (80%), each significantly less likely than the last to be aware of the program.

Some perspective on this relationship can be drawn from the information sources of the unaided awareness section. Arden $_{(EJ)}$ residents were more likely than the other two EJ neighborhoods to cite multiple sources of information, which corroborates the claim earlier that repeated exposure increases awareness. Moreover, Arden (EJ) residents were marginally more likely to cite the website as a source of information. Citing the website demonstrates prior awareness and active information seeking, unlike television, radio, or newspaper where a respondent may happen upon information by chance. The website citation helps to confirm the high rate of awareness for the Check Before You Burn program.

Figure 36: Total Awareness - Neighborhood [All respondents]



*indicates statistically significant difference between groups

Compliance

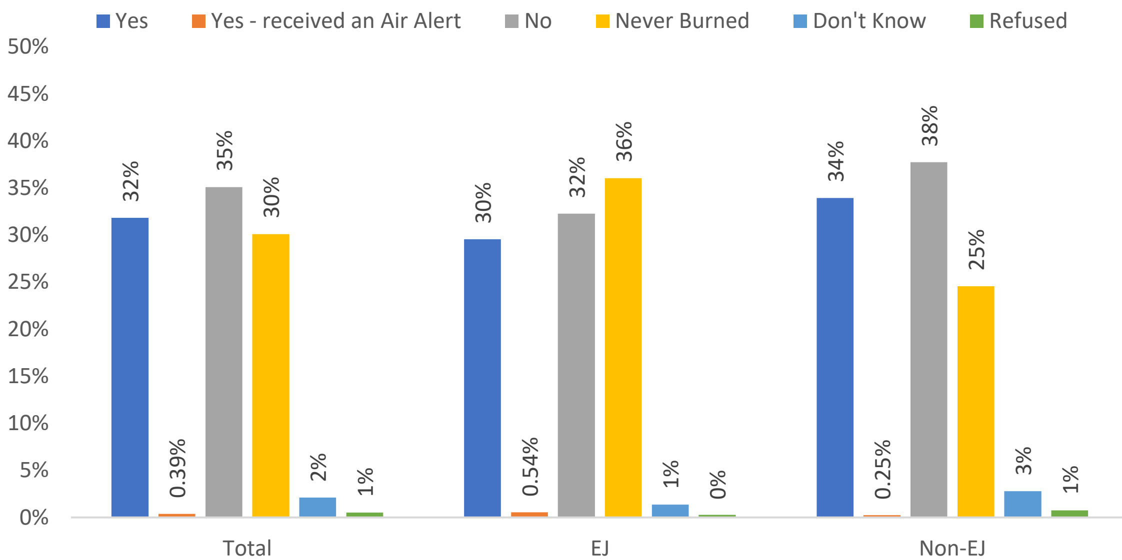
If a respondent said they were aware of the program, they were asked a subsequent compliance question:

> *And did you reduce the number of fires you burned this winter because you heard or saw a notice not to burn wood?*

A look at compliance rates shows very few differences between EJ and Non-EJ communities. Overall, compliance among aware respondents is 32%. For EJ community residents, 30% claimed compliance, while 34% claimed compliance in the Non-EJ community. Chi Square ($p < 0.05$) confirms this difference is statistically significant.

Also arising as a significant difference between EJ and Non-EJ community compliance is in those who report never burning at all. The EJ community was more likely to say they didn't burn at all (36% EJ vs 25% Non-EJ) and so had no opportunity to comply.

Figure 37: Compliance - EJ vs Non-EJ
[Aware respondents]

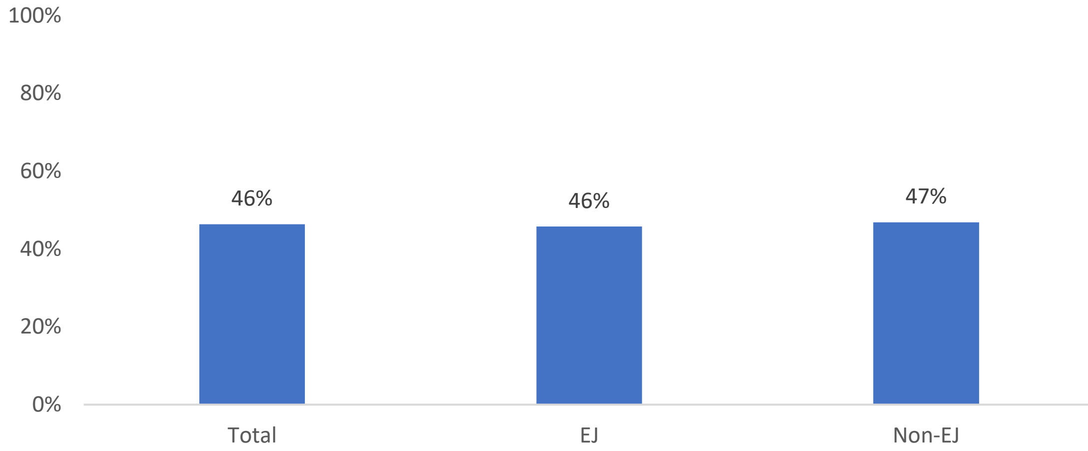


*indicates statistically significant difference between groups

Since the compliance rates can appear skewed when viewed among all respondents whether they burn or not, compliance rates among burners only is displayed next.

In total, 46% of burners said they reduced the number of fires they burned over winter because they were aware of a notice not to burn wood. Chi Square ($p = 0.79$) found no significant difference between EJ and Non-EJ community respondents saying they complied: 46% EJ vs. 47% Non-EJ.

Figure 38: Compliance - EJ vs Non-EJ Burners
[Aware respondents who burned with their device]



Appendix A: Demographics

[ASK ALL RESPONDENTS]

8.0 How many people are living in your household?

	Total	EJ				Non-EJ			
		Total	Arden	S Natomas	S Sacramento	Total	Del Paso	T Street	Tahoe Park
n=	900	444	44	81	319	456	298	30	128
1) Live alone	20.4%	19.6%	20.5%	19.8%	19.4%	21.3%	21.1%	16.7%	22.7%
2) 2	33.8%	31.5%	45.5%	24.7%	31.3%	36.0%	37.2%	46.7%	30.5%
3) 3	16.3%	15.8%	20.5%	19.8%	14.1%	16.9%	15.8%	20.0%	18.8%
4) 4	14.4%	14.2%	4.5%	16.0%	15.0%	14.7%	14.1%	13.3%	16.4%
5) 5 or more	13.2%	17.8%	6.8%	19.8%	18.8%	8.8%	8.7%	0.0%	10.9%
9) Non-response (Don't know/Refused)	1.8%	1.1%	2.3%	0.0%	1.3%	2.4%	3.0%	3.3%	0.8%

[ASK ALL RESPONDENTS]

8.1 Please stop me when I reach the category that includes your age.

	Total	EJ				Non-EJ			
		Total	Arden	S Natomas	S Sacramento	Total	Del Paso	T Street	Tahoe Park
n=	900	444	44	81	319	456	298	30	128
1) 18 – 24	2.3%	3.4%	0.0%	3.7%	3.8%	1.3%	0.7%	3.3%	2.3%
2) 25 – 34	8.7%	10.8%	15.9%	16.0%	8.8%	6.6%	4.4%	16.7%	9.4%
3) 35 – 44	12.0%	12.6%	9.1%	17.3%	11.9%	11.4%	9.1%	20.0%	14.8%
4) 45 – 54	15.0%	12.2%	11.4%	13.6%	11.9%	17.8%	16.1%	23.3%	20.3%
5) 55 – 64	24.0%	25.2%	31.8%	24.7%	24.5%	22.8%	22.1%	23.3%	24.2%
6) 65 & older	35.4%	34.0%	31.8%	23.5%	37.0%	36.8%	44.3%	10.0%	25.8%
9) Non-response (Don't know/Refused)	2.6%	1.8%	0.0%	1.2%	2.2%	3.3%	3.4%	3.3%	3.1%

[ASK ALL RESPONDENTS]

8.2 What is the highest level of education you have completed?

	Total	EJ				Non-EJ			
		Total	Arden	S Natomas	S Sacramento	Total	Del Paso	T Street	Tahoe Park
n=	900	444	44	81	319	456	298	30	128
1) High school or less	16.4%	22.5%	9.1%	21.0%	24.8%	10.5%	7.7%	3.3%	18.8%
2) Some college	22.7%	26.8%	29.5%	19.8%	28.2%	18.6%	14.8%	16.7%	28.1%
3) Trade or vocational school – no college	3.4%	4.3%	0.0%	4.9%	4.7%	2.6%	2.0%	0.0%	4.7%
4) College degree	36.2%	32.9%	38.6%	39.5%	30.4%	39.5%	43.0%	36.7%	32.0%
5) Post graduate degree	18.6%	11.0%	22.7%	14.8%	8.5%	25.9%	29.5%	40.0%	14.1%
9) Non-response (Don't know/Refused)	2.7%	2.5%	0.0%	0.0%	3.4%	2.9%	3.0%	3.3%	2.3%

[ASK ALL RESPONDENTS]

8.3 Please stop me when I reach the category that best describes your ethnic background

	Total	EJ				Non-EJ			
		Total	Arden	S Natomas	S Sacramento	Total	Del Paso	T Street	Tahoe Park
n=	900	444	44	81	319	456	298	30	128
1) African-American	8.9%	15.1%	4.5%	12.3%	17.2%	2.9%	1.3%	0.0%	7.0%
2) Asian/Pacific Islander	4.6%	7.2%	0.0%	1.2%	9.7%	2.0%	1.7%	0.0%	3.1%
3) Caucasian	61.0%	45.7%	68.2%	58.0%	39.5%	75.9%	82.6%	76.7%	60.2%
4) Hispanic/Latino	13.4%	19.4%	15.9%	19.8%	19.7%	7.7%	2.3%	10.0%	19.5%
5) Russian	0.3%	0.5%	0.0%	0.0%	0.6%	0.2%	0.3%	0.0%	0.0%
6) Something else [CAPTURE RESPONSE]	5.7%	6.5%	4.5%	3.7%	7.5%	4.8%	4.7%	10.0%	3.9%
9) Non-response (Don't know/Refused)	6.1%	5.6%	6.8%	4.9%	5.6%	6.6%	7.0%	3.3%	6.3%

[ASK ALL RESPONDENTS]

8.4 And finally, please stop me when I read the category that best describes your TOTAL household income before taxes for 2015.

	Total	EJ				Non-EJ			
		Total	Arden	S Natomas	S Sacramento	Total	Del Paso	T Street	Tahoe Park
n=	900	444	44	81	319	456	298	30	128
1) Under $20,000	5.7%	7.9%	6.8%	3.7%	9.1%	3.5%	2.0%	0.0%	7.8%
2) $20,000 to less than $40,000	15.4%	20.9%	13.6%	17.3%	22.9%	10.1%	6.4%	3.3%	20.3%
3) $40,000 to less than $60,000	17.8%	21.8%	18.2%	22.2%	22.3%	13.8%	12.4%	6.7%	18.8%
4) $60,000 or to less than $100,000	22.2%	23.0%	25.0%	29.6%	21.0%	21.5%	21.5%	33.3%	18.8%
5) $100,000 or more	22.1%	13.3%	27.3%	17.3%	10.3%	30.7%	33.6%	50.0%	19.5%
9) Non-response (Don't know/Refused)	16.8%	13.1%	9.1%	9.9%	14.4%	20.4%	24.2%	6.7%	14.8%

9.0 Neighborhood

	Total	EJ				Non-EJ			
		Total	Arden	S Natomas	S Sacramento	Total	Del Paso	T Street	Tahoe Park
n=	900	444	44	81	319	456	298	30	128
1) Arden	4.9%	7.9%	100.0%	0.0%	0.0%	3.5%	0.0%	0.0%	0.0%
2) Del Paso Manor	33.1%	20.9%	0.0%	0.0%	0.0%	10.1%	100.0%	0.0%	0.0%
3) South Natomas	9.0%	21.8%	0.0%	100.0%	0.0%	13.8%	0.0%	0.0%	0.0%
4) South Sacramento	35.4%	23.0%	0.0%	0.0%	100.0%	21.5%	0.0%	0.0%	0.0%
5) T Street (Non-EJ)	3.3%	13.3%	0.0%	0.0%	0.0%	30.7%	0.0%	100.0%	0.0%
9) Tahoe Park-Colonial Heights	14.2%	13.1%	0.0%	0.0%	0.0%	20.4%	0.0%	0.0%	100.0%

Appendix B: Questionnaire

Final Wood Burning Toxics Community Survey - Winter 2016/17

METHODOLOGY:

Field Dates:	• Mid December 2016 and/or Early Jan 2017
Sample Size:	• 900 completed interviews (450 cell and 450 landlines)
Sampling Error (calculated at 95% confidence level):	• +/- 3.3% for 900
Unit of Analysis:	• Head of Households in Sacramento County in which an indoor (or outdoor) wood (or pellet) burning device exists
Language:	• English, Spanish, and Russian
Sampling Frame:	• RDD purchased sample, proportionally representative of population
Quotas:	• Gender 50/50
Average Length of Interview:	• 8 minutes

● INTRODUCTION ●

Hello, my name is _______________ from Meta Research, a public opinion research firm. We are conducting a survey about air quality issues facing our local area. This is not a solicitation and you will not be asked to buy anything.

May I speak to the someone in your household who is presently at home and is considered to be a head of household?
[If head of household] Can you take time now for a confidential interview?

[When speaking with head of household] Hello, my name is _______________ from Meta Research, a public opinion research firm. We are conducting a survey about air quality issues facing our local area. This is not a solicitation and you will not be asked to buy anything. Can you take time now for a confidential interview?

[IF NO HEAD OF HOUSEHOLD AVAILABLE, SCHEDULE CALL BACK TIME]

[IF NECESSARY: It should take approximately 8 minutes, depending on your responses.]

[IF NECESSARY: Everything you tell me will be completely confidential. You have the right to refuse to answer any question at any time. I can conduct the interview right now, or we can make an appointment for me to call you back at a more convenient time.]

[IF NECESSARY: We can share the name of sponsor at the end of the survey so as not to bias your responses.]

[IF NECESSARY: This is a research study and I'm only interested in your opinions as a Sacramento area resident. At no time will I try to sell you anything.]

• DATABASE INFORMATION •

DB1. ZIP Code (FROM SAMPLE):

• SCREENING QUESTIONS •

READ TO ALL

Thank you. This call may be monitored for quality control purposes.

S1. To confirm, can you tell me your zip code?

[RECORD RESPONSE]

[ASK ALL RESPONDENTS]

S2. And, do you have a wood-burning device in or outside your home; such as a fireplace, a wood or pellet stove; or an outdoor fire?

[NOTE TO INTERVIEWER: WE ARE LOOKING TO SPEAK WITH THOSE WHO HAVE THE CAPABILITY TO BURN WOOD OR PELLETS. INDOOR GAS UNITS AND OUTDOOR BARBEQUES OF ANY KIND DO NOT COUNT]

1. Yes (continue)
2. Yes but just a barbeque (volunteered) (THANK & TERMINATE)
3. No (THANK & TERMINATE)

8) Don't know (THANK & TERMINATE)
9) Refused (THANK & TERMINATE)

[ASK IF S2 =1]

S3. And what wood-burning device or devices do you have? (Interviewer record all that apply: multi-punch)

1) Indoor fireplace (burns wood, pellets, or logs – NOT gas)
2) Fireplace insert
3) Wood or pellet stove
4) Outdoor wood burning fire pit
5) Chiminea [pronounced chee-men-A-uh] [Thank and Terminate if this is the ONLY device]
6) Outdoor Barbeque: [Thank and Terminate if this is the ONLY device]
8) Don't know (VOLUNTEER)
9) Refused

[ASK IF S3 =1]

S3. Is burning wood or pellets the only possible way to heat your home or can you heat it with another permanent heat source?

1) Wood-burning is the only heat source [THANK & TERMINATE]
2) Other sources available to heat home [CONTINUE]

8) Don't know / Undecided [VOLUNTEERED] [THANK & TERMINATE]
9) Refused [VOLUNTEERED] [THANK & TERMINATE]

[ALL RESPONDENTS]
S4. [BY OBSERVATION] Gender [QUOTAS: 50/50 SPLIT]

1) Female
2) Male

[ALL RESPONDENTS]
S5. [BY OBSERVATION] Language

1) English
2) Spanish
3) Russian

• SURVEY BEGINS •

• AIR QUALITY ISSUES •

[ASK ALL RESPONDENTS]
1.1 Now, I'd like to talk about air quality issues in the Sacramento area. Using the scale, not at all [1], somewhat [2], or very unhealthy [3], how would you rate the contribution to WINTERTIME air pollution caused by ____________________ in the Sacramento area?

[IF NECESSARY: And by winter, I mean from November through February? [FOR NEXT: And how would you rate the seriousness of WINTERTIME air pollution caused by ____?]

[CATEGORIES FOR CODING]
1) Not at all unhealthy
2) Somewhat unhealthy
3) Very unhealthy
8) Undecided/Don't know [VOLUNTEERED]
9) Refused

RANDOMIZE
a. traffic
b. industry
c. agricultural burning
d. residential wood burning fireplaces

• WOOD BURNING ACTIVITY •

"Now let's talk about your wood burning activity this winter, that is, from late November to today."

[ASK IF S3 = 1]
4.0a In general, would you say you burned wood, pellets, or manufactured logs in your indoor fireplace ____ [READ LIST

1) Less than once a week
2) About once a week
3) Two or more times a week
4) Mainly on Friday and Saturday nights
5) Mainly on Holidays
6) Not at all

8) Other
9) Don't know/Undecided [VOLUNTEERED]
10) Refused [VOLUNTEERED]

[ASK IF S3 = 1 & 4.0a = 1, 2, 3, 4, 5, or 8]
4.0b And typically, what time of the day do you burn with your indoor fireplace? Day, night, or both?

1) Day (6 am to 6 pm)
2) Night (6 pm to 6am)
3) Day and night

8) Other [RECORD RESPONSE]
9) Don't know/Undecided [VOLUNTEERED]
10) Refused [VOLUNTEERED]

[ASK IF S3 = 1 & 4.0a = 1, 2, 3, 4, 5, or 8]
4.0c Do you have an Environmental Protection Agency certified indoor fireplace?

1) It is certified
2) Not certified

8) Don't know [VOLUNTEERED]
9) Refusal [VOLUNTEERED]

[ASK IF S3 = 2]
4.1a In general, would you say you burned wood, pellets, or manufactured logs in your fireplace insert ____ [READ LIST

1) Less than once a week
2) About once a week
3) Two or more times a week
4) Mainly on Friday and Saturday nights
5) Mainly on Holidays
6) Not at all

8) Other
9) Don't know/Undecided [VOLUNTEERED]
10) Refused [VOLUNTEERED]

[ASK IF S3 = 2 & 4.1a = 1, 2, 3, 4, or 5]
4.1b And typically, what time of the day do you burn with your fireplace insert? Day, night, or both?

1) Day (6 am to 6 pm)
2) Night (6 pm to 6am)
3) Day and night

8) Other [RECORD RESPONSE]
9) Don't know/Undecided [VOLUNTEERED]
10) Refused [VOLUNTEERED]

[ASK IF S3 = 2 & 4.1a = 1, 2, 3, 4, 5, or 8]
4.1c Do you have an Environmental Protection Agency certified fireplace insert?

1) It is certified
2) Not certified

8) Don't know [VOLUNTEERED]
9) Refusal [VOLUNTEERED]

[ASK IF S3 = 3]
4.2a In general, would you say you burned wood, pellets, or manufactured logs in your wood or pellet stove_____ [READ LIST

1) Less than once a week
2) About once a week
3) Two or more times a week
4) Mainly on Friday and Saturday nights
5) Mainly on Holidays
6) Not at all

8) Other
9) Don't know/Undecided [VOLUNTEERED]
10) Refused [VOLUNTEERED]

[ASK IF S3 = 3 & 4.2a = 1, 2, 3, 4, or 5]
4.2b And typically, what time of the day do you burn with your wood or pellet stove? Day, night, or both?

1) Day (6 am to 6 pm)
2) Night (6 pm to 6am)
3) Day and night

8) Other [RECORD RESPONSE]
9) Don't know/Undecided [VOLUNTEERED]

10) Refused [VOLUNTEERED]

[ASK IF S3 = 3 & 4.2a = 1, 2, 3, 4, 5, or 8]
4.2c Do you have an Environmental Protection Agency certified wood or pellet stove?

1) It is certified
2) Not certified

8) Don't know [VOLUNTEERED]
9) Refusal [VOLUNTEERED]

[ASK ALL RESPONDENTS]
4.1 And in general would you say you burned less, the same, or more wood, pellets or manufactured logs this past winter as compared with a typical winter?

[Interviewer: This includes both indoor and outdoor devices]

1) Less
2) Same
3) More

8) Don't know/Undecided [VOLUNTEERED]
9) Refused [VOLUNTEERED

4.3 And in general, where did you get the wood, pellets, or manufactured logs you've burned this winter?

1) Grocery Store
2) Hardware Store
3) Wood Dealer
4) Got it free

8) Other
9) Don't know/Undecided [VOLUNTEERED]
10) Refused [VOLUNTEERED]

• AWARENESS OF PM POLLUTION& NO BURN •

[ASK ALL RESPONDENTS]

5.0 This winter, did you hear, read, or see anything informing residents not to use their wood burning fireplaces or outdoor fire pits because of poor air quality?

[IF NECESSARY: Again by winter, I'm talking about late November.]

1) Yes
2) No

8) Don't know/Undecided [VOLUNTEERED]
9) Refused [VOLUNTEERED]

[ASK IF 5.0=1]

5.1 And where did you read, see or hear this information?

CATEGORIES FOR CODING

1) Facebook
2) Twitter
3) Website
4) Mobile app
5) Air Alert email
6) Phone recording
7) Newspaper
8) Television
9) Radio
10) Word of Mouth
11) Other (Specify)
12) Don't Know
13) Refused

[ASK IF 5.0=1]

5.2 And did you reduce the number of times you burned this winter because you heard or saw a notice not to burn wood?

[IF NECESSARY: Again by winter, I'm talking since the beginning of December.]

1) Yes
2) No
3) Yes – received an Air Alert [VOLUNTEERED]
4) Never burned

8) Don't know/Undecided [VOLUNTEERED]
9) Refused [VOLUNTEERED]

[READ if 5.0 = 2, 8 or 9]

You may or may not have heard that in Sacramento County, it's the law that from November through February residents and businesses are prohibited from using indoor or outdoor fireplaces, wood stoves, and fire pits that burn wood, pellets, manufactured logs or any other solid fuel on days when air quality is forecast to be unhealthy to breathe. It is your responsibility to Check Before You Burn, to see if it is permissible to light a fire.

[ASK IF 5.0 = 2, 8 or 9]
5.3 Does this now sound familiar to you?
CATEGORIES FOR CODING:

1) Yes
2) No

8) Undecided/Don't know [VOLUNTEERED]
9) Refusal [VOLUNTEERED]

[ASK IF 5.3 = 1]
5.4 And did you reduce the number of fires you burned this winter because you heard or saw a notice not to burn wood?
[IF NECESSARY: Again by winter, I'm talking since the beginning of December.]

1) Yes
2) No
3) Yes – received an Air Alert [VOLUNTEERED]
4) Never burned

8) Don't know/Undecided [VOLUNTEERED]
9) Refused [VOLUNTEERED]

DEVICE CHARACTERISTICS

[ASK ALL RESPONDENTS]

6.0 Are you aware that you can apply for a sole source of heat or economic hardship waiver to be considered exempt from burn bans if you are approved by the Air District?

1) Yes
2) No
3) Yes, already exempt (Volunteered)

8) Don't Know/Undecided (Volunteered)
9) Refused (Volunteered)

[ASK ALL RESPONDENTS]

7.0 Are you aware of the complaint line to call to alert the Sacramento Air District if you see someone burning on a day when burning is prohibited?

1) Yes
2) No

• DEMOGRAPHICS •

"Now just a few final questions for statistical purposes… "

[ASK ALL RESPONDENTS]
8.0 How many people are living in your household?

1) Live alone
2) 2
3) 3
4) 4
5) 5 or more
9) Non-response (Don't know/Refused)

[ASK ALL RESPONDENTS]
8.1 Please stop me when I reach the category that includes your age.
[READ CHOICES]

1) 18 – 24
2) 25 – 34
3) 35 – 44
4) 45 – 54
5) 55 – 64
6) 65 & older
9) Non-response (Don't know/Refused)

[ASK ALL RESPONDENTS]
8.2 What is the highest level of education you have completed?
[IF NECESSARY: READ CHOICES]

1) High school or less
2) Some college
3) Trade or vocational school – no college
4) College degree
5) Post graduate degree
9) Non-response (Don't know/Refused)

[ASK ALL RESPONDENTS]
8.3 Please stop me when I reach the category that best describes your ethnic background.
[NOTE: ORDER IS ALPHABETICAL]

1) African-American
2) Asian/Pacific Islander
3) Caucasian
4) Hispanic/Latino
5) Russian
6) Something else [CAPTURE RESPONSE]
9) Non-response (Don't know/Refused)

[ASK ALL RESPONDENTS]
8.4 And finally, please stop me when I read the category that best describes your TOTAL

household income before taxes for 2013.

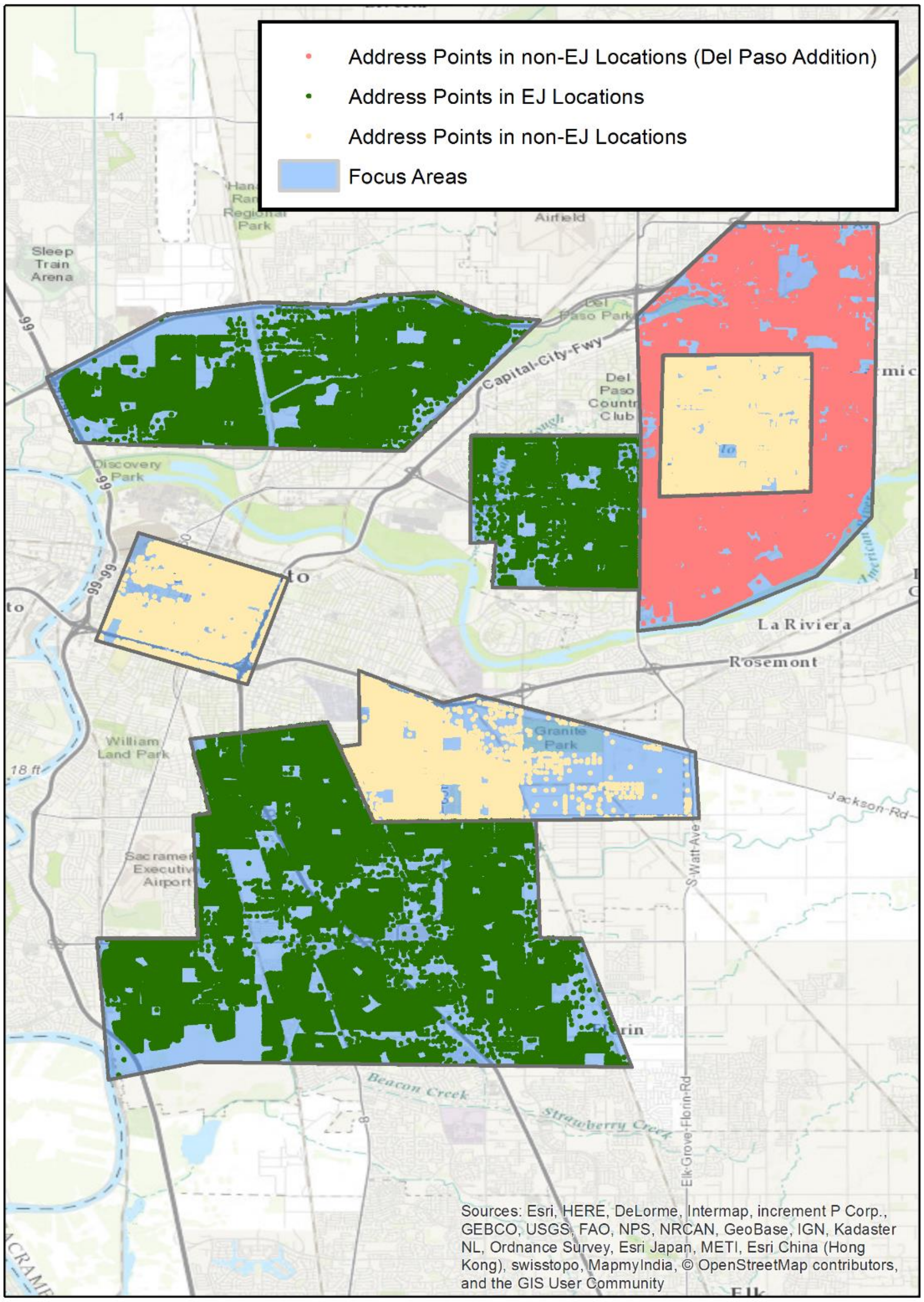
1) Under $20,000
2) $20,000 to less than $40,000
3) $40,000 to less than $60,000
4) $60,000 or to less than $100,000
5) $100,000 or more
9) Non-response (Don't know/Refused)

That's the end of our survey. This has been a confidential interview conducted by ________ at Meta Research. You may be called by someone from Meta Research to verify that this interview was conducted. May I please have just your first name for verification purposes [RECORD]? Thank you very much for your time and have a good evening

If asked, this survey is being conducted for

Sacramento Metropolitan Air Quality Management District

Appendix C: Map of Targeted Locations



Appendix B. Supporting Material for AirBeam $PM_{2.5}$

B.1 Sensor Precision and Correction

Table B-1 shows statistics related to precision and the correction factors for the AirBeam low-cost sensors.

Table B-1. Precision statistics of R^2 values, linear regression intercepts, and slopes, using collocated measurements from the pre- and post-study periods. The normalization correction factor was taken to be the linear regression using the average slope and intercept.

AirBeam	Pre-Study N (Hrs of Valid Data)	Pre-Study R Squared Versus AirBeam Means	Pre-Study Slope of Regression	Pre-Study Intercept of Regression	Post-Study N (Hrs of Valid Data)	Post-Study R Squared Versus AirBeam Means	Post-Study Slope	Post-Study Intercept	Correction Factor Slope: Average Slope	Correction Factor Intercept: Average Intercept
13th Ave.	47	1.00	0.92	0.03	470	1.00	0.96	-0.19	0.94	-0.08
24th Ave.	47	1.00	0.93	-0.54	469	1.00	0.96	-0.49	0.95	-0.51
64th St.	152	1.00	1.01	0.94	467	1.00	1.06	0.10	1.04	0.52
ARB T St. 2	146	1.00	0.81	-0.16	467	0.99	0.75	0.07	0.78	-0.04
ARB T St. 3	150	1.00	0.95	1.19	467	1.00	1.02	0.15	0.99	0.67
Alderwood	150	1.00	0.88	1.51	465	1.00	0.96	0.09	0.92	0.80
Coroval	138	1.00	1.15	0.16	378	1.00	1.26	-0.70	1.21	-0.27
DPM2	152	1.00	0.80	2.64	465	0.99	0.87	1.37	0.84	2.01
DPM3	152	1.00	1.11	-0.53	468	1.00	1.19	-0.79	1.15	-0.66
Darwin St.	88	1.00	0.99	0.56	466	1.00	1.04	-0.23	1.02	0.17
Henrietta	47	1.00	1.55	-1.18	291	0.99	1.73	-0.52	1.64	-0.85
Socorro	88	1.00	0.96	0.74	464	1.00	1.01	-0.22	0.99	0.26
Tristan Cir.	138	0.99	0.97	-2.95	466	0.98	0.95	-1.01	0.96	-1.98
Wyman	47	0.99	1.10	1.17	467	0.99	1.08	1.25	1.09	1.21
79th St.	62	1.00	0.94	-0.39	466	1.00	0.85	-0.71	0.89	-0.55
ARB T St.	146	1.00	1.14	-1.68	392	1.00	1.07	-0.35	1.10	-1.01
DPM	152	1.00	1.13	0.10	150	1.00	1.06	0.44	1.13	0.10
Hermosa St.	47	0.99	0.85	-0.30	291	0.99	0.83	-0.16	0.85	-0.30
T St. Tier 3	152	0.99	1.09	-3.21	291	1.00	0.98	-0.31	1.09	-3.21

B.2 Comparison of Sensor PM to Collocated BAM and FRM Measurements with Multi-Variate Linear Regression

In order to evaluate meteorological impact further, multi-variate linear regression was performed between AirBeam measurements and the regulatory monitor measurements, using meteorological variables at Del Paso Manor as explanatory variables for both hourly measurements and 24-hour average values. **Table B-2** shows the improvement to the adjusted R^2 values via linear regression. The improvement from each individual meteorological variable is shown, as well as all four variables, and the quadratic of all four variables, e.g., the square of temperature. Dew point and relative humidity are the most important explanatory variables for these three cases, showing the biggest improvements in the adjusted R^2 values for both the BAM 1020 and the FRM. This means that the deviation between the AirBeam measurements and the measurements from regulatory monitors showed the highest correlation to dew point and relative humidity.

The same methodology was applied to collocated measurements at T Street during the study period, showing similar relationships. At T Street, hourly measurements between an AirBeam and the BAM 1020 had an R^2 of 0.68, and daily average measurements between the same two instruments had an R^2 of 0.75. These values show that the AirBeams demonstrated comparable modest accuracy compared to the reference instruments at both collocation sites. Multi-variate linear regression was performed at T Street using the same four meteorological variables as at Del Paso Manor. However, improvements from this technique are site-specific to Del Paso Manor or T Street, and applying one set of corrections to the measurements at the other site does not improve the initial correlation; therefore, no further correction to AirBeam values was applied.

Table B-2. Multi-linear regressions from the study period using collocated Del Paso Manor measurements. Rows show the initial R^2 between one AirBeam and the regulatory monitor, and the improvement with meteorological explanatory variables.

Variables of Regression	Hourly BAM vs. AirBeam: Adjusted R Squared	Daily Average BAM vs. AirBeam: Adjusted R Squared	Daily FRM vs. AirBeam Adjusted R Squared
Initial R Squared	0.601	0.573	0.709
REG* + Temp	0.604	0.596	0.732
REG + Dew	0.623	0.641	0.766
REG + RH	0.617	0.647	0.76
REG + Ws	0.609	0.567	0.704
REG + Temp + Dew + RH + Ws	0.648	0.651	0.763
REG + quadratic(Temp,Dew,RH,WS)	0.732	0.83	0.883

*REG denotes the regulatory monitor: BAM for the first two columns and FRM for the third column.

B.3 Sensor PM Inter-Site Comparisons

Table B-3 shows the results of the Pairwise Wilcoxon Rank comparison for all pairwise EJ vs. non EJ AirBeam comparisons. When all EJ sites are grouped together and compared to all non-EJ sites grouped together, there is no significant difference in PM concentrations, as also seen with BC.

Table B-3. Matrix showing the p-value results of the Pairwise Wilcoxon Rank test for EJ (first column) vs. non-EJ (top row) AirBeams. A p-value equal to 1 indicates that no statistical difference in the mean between the two sites can be determined. A p-value less than 0.05 indicates that a difference in the mean is significant at the 95% confidence level.

	Alderwood	ARB T St.	DPM	T St. Tier 3	Wyman	13th Ave	64th St	79th St
Coroval	1	1	0.13898	1	0.65712	1	1	0.00125
Darwin St	1	0.67621	1	1	1	1	1	1
Henrietta Dr.	1	1	1	1	1	1	1	0.06066
Hermosa St.	1	0.73874	1	1	1	1	1	1
Socorro Way	1	1	1	1	1	1	1	0.13343
Tristan Cir	1	0.00046	1	0.45039	1	1	1	1
24th Ave	1	1	1	1	1	1	1	0.04104