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Exposure Experiences Among Impacted Communities and Farmworkers in Northern California: A Mixed Methods Investigation of Air Pollution Exposures, Perceptions, and Report-Back Methods

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by

Marley Zalay

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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University of California, Berkeley

Committee in Charge:

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Professor Rachel Morello-Frosch
Professor Ajay Pillarisetti

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Abstract

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The many successful efforts to reduce air pollution in California since the 1990s through regulations from the California Air Resources Board (CARB) initially targeted on-road vehicles; however, air pollution is not equally distributed, and some populations still experience greater exposure burdens than others. Two populations disproportionately exposed to air pollution were examined in Northern California: communities of Stockton and Fresno, who experience historically poor air quality because of trapped air pollution in the Joaquin Valley; and farmworkers who use off-road diesel-powered agricultural equipment, and whose exposure to carcinogenic diesel exhaust has been poorly characterized. We conducted exposure assessments for three different air pollutants: polycyclic aromatic hydrocarbons (PAHs), nitrogen dioxide (NO_2), and diesel particulate matter, measured as black carbon (BC). Participants in Stockton and Fresno were recruited within the San Joaquin Valley Pollution and Health Environmental Research (SPHERE) Study to characterize residential exposures to air pollutants. Additionally, the Agricultural Off-Road Diesel Equipment (ACRE) Pilot Study was funded and conducted as part of this doctoral research. Within the ACRE Pilot Study, we assessed occupational exposure to diesel exhaust, perceptions of work and exposure, and attitudes about report-back of personal exposure results among farmworkers. Our findings demonstrated infiltration of outdoor PAH concentrations into home environments in Stockton and Fresno, which may have been facilitated by opening windows and home type, as well as a seasonal effect with higher outdoor concentrations in the spring compared to summer and fall months. We identified sources of indoor exposure to PAHs, including burning candles, using gas-powered heaters, and smoking or vaping in the home. Older tractors resulted in higher concentrations of measured air pollutants than newer tractors. Results also show that farmworkers may be more highly exposed to diesel exhaust than the general public and farmers and that more training for farmworkers about diesel exhaust and exposure reduction strategies is warranted. Most farmworkers in the study wanted their personal exposure results and reported that a short explanatory video aided in their understanding of report-back documents. This dissertation elucidates sources of exposure and opportunities for exposure reduction in marginalized populations exposed to air pollutants at home and at work.

This work is dedicated to the participants of this research and the larger community of Californians facing air pollution exposure at home and at work.

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Chapter 1. Polycyclic Aromatic Hydrocarbon and Diesel Exhaust Exposure Among Disproportionately Burdened Populations of Northern California and the Opportunity for Report-Back

1.1 Background

Mobile emission sources, including on-road vehicles and off-road equipment, are the largest contributors of air pollution in California, generating approximately 80% of nitrogen oxides, 90% of diesel particulate matter, and nearly 40% of the state's greenhouse gas emissions.[1] The many successful efforts to reduce air pollution in California since the 1990s through regulations from the California Air Resources Board (CARB) initially targeted on-road vehicles.[2] Air pollution, however, is not equally distributed, and some populations still experience greater exposure burdens than others.[1] Two populations disproportionately exposed to air pollution were examined in this dissertation: farmworkers in Northern California and communities in the San Joaquin Valley.

Communities in the San Joaquin Valley of California have historically experienced poor air quality due to the valley's topography and surrounding mountain ranges that trap air pollution.[3] The local San Joaquin Valley Air Pollution Control District has failed to meet federal particulate matter air quality standards for over twenty years.[4–6] The San Joaquin Valley, in particular, is one of only two areas in the nation experiencing extreme ozone nonattainment.[7] Even with increasingly stringent emission standards on engine manufacturers from the U.S. Environmental Protection Agency (EPA), diesel exhaust from agricultural vehicles and equipment represents a significant source of air pollution in California, and accounts for 29% of diesel particulate matter emissions in the state. Off-road vehicles and equipment, which include tractors, combines, water trucks, and other agricultural equipment, are expected to be the single largest contributor of diesel emissions in the state by 2030.[7,8] Farmworkers are at risk of air pollution exposures from working in close proximity to diesel-powered agricultural equipment, however their exposures have not been well-characterized.

In this dissertation, exposure assessments for three different air pollutants are presented: polycyclic aromatic hydrocarbons (PAHs), nitrogen dioxide (NO_2), and diesel particulate matter, measured using black carbon (BC) as a surrogate. PAHs are a class of semi-volatile air pollutant compounds formed from incomplete combustion and come from many of the same sources as particulate matter.[9] PAHs investigated in this study included naphthalene (NAP), fluorene (FLU), phenanthrene (PHE), anthracene (ANT), and pyrene (PYR), which represent five out of the sixteen PAHs designated by the U.S. EPA as High Priority Pollutants.[10] NAP is classified as a possible human carcinogen by the International Agency for Research on Cancer (IARC), and FLU and ANT indicate carcinogenicity risk in animal studies.[11,12] Exposure to PHE has been associated with adverse immunological effects in humans; in animal studies, it has caused liver, lung, kidney, and reproductive system toxicity and reduced immune function.[13,14,15,16,17] PAHs are often produced in mixtures along with other gases and particulate matter produced via combustion, including NO_2 and BC.[18] NO_2 is a respiratory irritant that is associated with reduced respiratory function and immune function.[19–21] BC has been associated with adverse cardiovascular, respiratory and neurological outcomes in epidemiological research, as well as increased morbidity and premature mortality..[22,23] In addition to being associated with adverse health effects, BC also contributes to climate change; NO_2 contributes to the production of smog, ultrafine particles and the greenhouse gas, nitrous oxide, via secondary formation.[24]

Specifically, the exposure assessments in this dissertation were conducted among populations in Northern California experiencing disproportionate air pollution burdens, socio-economic stressors, and health disparities. In combination, these burdens are referred to as cumulative impacts. Environmental justice, as defined by the U.S. EPA, means that no group of people should bear a disproportionate share of adverse environmental pollution or other consequences resulting from industrial, governmental, or commercial operations or policies.[25] In an effort to advance environmental justice, two cities in the San Joaquin Valley, Stockton and Fresno, were selected into the Community Air Protection Program, implemented as a result of California Assembly Bill 617 (passed in 2017) to reduce air pollutant exposures in disadvantaged communities most heavily impacted by air pollution across the state.[26,27] Residents in the San Joaquin Valley have some of the highest asthma rates in the state, with over half of residents covered by Medi-Cal, and 18% living below the federal poverty level.[28,29] Farmworkers also experience cumulative impacts; between one third and one half of farmworkers expressed having at least one chronic health condition in a 2022 survey, including asthma, diabetes, hypertension, anxiety, and depression.[30] Farmworkers also face unique stressors related to job security, immigration status, financial challenges and poverty, social isolation, and inequitable access to resources such as health insurance, high-quality housing, and transportation.[31,32,33]

Previous research has documented the benefits of communicating study findings to participants ("report-back"), including increased engagement and trust in research, improved knowledge and awareness of environmental health, and greater likelihood of using study results to adopt health-protective behaviors or engage in advocacy.[34,35] Report-back promotes data democratization while often increasing participants' understanding of exposure risks and how to protect themselves, a core component of environmental health literacy.[34] There is limited evidence indicating that these benefits also extend to marginalized and impacted populations because they have been underrepresented in research studies.[36,37]

1.2 Goals

This dissertation aims to understand sources of exposure and opportunities for exposure reduction among impacted populations to advance health equity. We conducted quantitative exposure assessments to address the gaps in our understanding of residential exposures to PAHs among Stockton and Fresno communities and occupational exposure to diesel exhaust among farmworkers. We also aimed to address gaps in the literature regarding how to report back study results to marginalized populations, such as farmworkers. To advance environmental health literacy and empower workers about how to reduce exposures to diesel exhaust, we conducted qualitative interviews for usability-testing of report-back materials.

1.3 Approach

Chapter 2 of this dissertation utilizes a subset of data from the San Joaquin Valley Pollution and Health Environmental Research (SPHERE) Study on residential exposures to PAHs. During the study, researchers collaborated with local community organizations (the Central California Asthma Collaborative and Little Manila Rising) to recruit participants and conduct field work in Fresno and Stockton. This study was funded by grants from the California Air Resources Board and the Office of Environmental Health Hazard Assessment. The SPHERE Study was the first in a residential setting to measure indoor and outdoor airborne PAHs and urinary biomarkers of PAHs to assess exposure via two complementary methods. In addition to assessing exposure to PAHs, the SPHERE Study also measured noise and other air pollutants, and these results are reported elsewhere.[38] Although long-term air monitoring for PAHs was conducted in Fresno over the past 20 years, no such monitoring has been conducted in most cities, including Stockton. Indoor concentrations of airborne PAHs during typical home occupancy have remained poorly characterized, representing a critical gap in understanding exposure sources and pathways.[39] Similarly, air pollutant exposures experienced by farmworkers are not well understood.

Chapters 3, 4 and 5 describe methods and results of the Agricultural Off-Road Diesel Equipment (ACRE) Pilot Study. This pilot study was made possible through funding from a grant from the California Labor Lab, a research collaborative funded by the National Institute of Occupational Safety and Health (NIOSH). Chapter 3 describes the farms and farmworkers that participated in the study and results of interviews with farmworkers. Recruitment of farms was conducted via word of mouth, attending workshops and conferences, and internet research. An effort was made to recruit farms that were representative of farms in California, including large farms, non-organic farms, and those that grew some of the largest crops produced in California: strawberries, grapes, nuts, lettuce, and tomatoes. Five agricultural operations growing apples, stone fruit, diversified vegetables, wine grapes, and table grapes in Mendocino, Yolo, Contra Costa, and Fresno counties participated in the study. Four of the five employers owned small- to medium-sized organic farms and one of the employers was a labor management company; there were no pesticides used on the crops while farmworkers employed by the labor management company participated in air monitoring. Farmworkers were recruited at these 5 locations in Northern California where employers granted researchers access. Farmworkers were also interviewed about attitudes about exposure, stress, workplace safety, whether they would like to receive their exposure results, and if so, what they would like to learn. This qualitative data aided in the interpretation of exposure results presented in Chapter 4 and the development of report-back materials presented in Chapter 5.

Chapter 4 reports the personal exposure concentrations to constituents of diesel exhaust among farmworkers. Although diesel exhaust is classified as a carcinogen by IARC, and diesel-powered tractors are ubiquitous on farms, exposures among farmworkers had not been characterized prior to this investigation. An attempt was made to recruit farms in the San Joaquin Valley because it contains over 50% of California's agricultural equipment;[7] we were able to recruit one employer in this region. We report our findings on the following constituents of diesel exhaust: NAP, PHE and ANT, BC and NO_2. We evaluated factors that affected the magnitude of exposure, including task, tractor age (Tier), and tractor tailpipe location and cab type to identify opportunities for exposure reduction.

Lastly, Chapter 5 discusses the process of developing worker-informed report-back materials and conducting interviews to evaluate the usability, accessibility, and understandability of report-back materials. There is a well-established and growing movement of researchers that cite benefits of report-back for both study participants and researchers; however, there have not been previous efforts or publications regarding returning diesel exhaust exposure results to farmworkers. Report-back is a tool that can help to address cumulative impacts that disadvantaged communities and disproportionately exposed populations experience. By empowering individual participants with information about how to take action to reduce exposure, report-back can further environmental health literacy (EHL), the process by which people seek out, comprehend, evaluate, and use environmental health information to make informed choices and prevent exposure for themselves or their community.[40] Involving study participants in the design of report-back materials and reporting back study results also aids in building trust and engagement between researchers and participants.[41,42] There are many reasons why underserved or disadvantaged populations, such as farmworkers, may distrust researchers or government agencies due to historical and current power imbalances and injustices in the healthcare sector.[43] A greater understanding of sources and variability that drive exposure among cumulatively impacted populations can inform exposure reduction and future interventions with the goal of advancing health equity.

Chapter 2. Household Exposure to Polycyclic Aromatic Hydrocarbons in the San Joaquin Valley of California

2.1 Introduction

The San Joaquin Valley of California **(Figure 1)** has historically experienced poor air quality due to its geographic location and has failed to meet federal particulate matter air quality standards for over twenty years.[4–6] Polycyclic aromatic hydrocarbons (PAH) are a class of semi-volatile air pollutant compounds formed from incomplete combustion and come from many of the same sources as particulate matter.[9] Unlike particulate matter, PAHs are not regulated as criteria air pollutants, but rather as toxic air contaminants. Outdoor sources of PAHs include combustion of wood and motor vehicle fuels, as well as charbroiling and industrial operations.[44,45] Indoor sources include smoking and vaping, home heating and cooking practices, and the use of some products such as moth balls and insect repellents.[46,47] PAHs are associated with myriad adverse health outcomes including, preterm birth, birth defects, increased HbA1c levels and evidence of metabolic dysfunction, cancer, as well as decreased pulmonary and immunological function among children.[48,9,47]

Air concentrations of four PAHs and their respective urinary metabolites were investigated inside and outside of 64 homes in Stockton and Fresno, two cities in the San Joaquin Valley. These PAHs — naphthalene (NAP), fluorene (FLU), phenanthrene (PHE), and pyrene (PYR) — represent four out of the sixteen PAHs designated by the US Environmental Protection Agency (EPA) as High Priority Pollutants.[10] NAP is classified as a possible human carcinogen by the International Agency for Research on Cancer (IARC), and exposure to PHE has been associated with adverse immunological effects.[13,14] FLU has been associated with increased DNA methylation of genes *F2RL3* and *AHRR,* indicating elevated lung cancer risk.[12] Exposure to PHE in mouse studies resulted in elevated inflammation in the liver and lung, increased risk of kidney fibrosis, and reproductive toxicity.[16,17]

Figure 1. Map of San Joaquin Valley showing Stockton (orange pin) and Fresno (blue pin)

NAP, FLU, and PHE exposures have been described among occupational groups;[49,50] however, community and residential exposures to PAHs are not well characterized. Many community-level PAH exposure estimates are based on ambient measurements collected outdoors, despite the fact that people spend a significant portion of their time inside residences.[51]

Further, PAHs are often produced in mixtures, making it difficult to disentangle the human health risk associated with exposure to each compound individually among humans.[9,52] Accurate, real-world assessment of community and residential exposures to PAHs is needed to understand how these exposures impact human health.

Fresno and Stockton experience disproportionate rates of asthma and cardiovascular disease, which are associated with air pollution exposures.[27,53] Many communities in the San Joaquin Valley, including Stockton and Fresno, are considered disadvantaged communities based on cumulative environmental and socioeconomic impacts they experience; over half of residents are covered by Medi-Cal, and 18% live below the federal poverty level.[26,28,29] Stockton and Fresno were selected into the Community Air Protection Program implemented as a result of California Assembly Bill 617 (passed in 2017) to reduce air pollutant exposures in communities most heavily impacted by air pollution across the state.[27]

Although PAHs are not routinely measured in ambient air by most U.S. regulatory agencies, and have not been consistently monitored in Stockton, long-term air monitoring over the past 20 years in Fresno funded by the California Air Resources Board (CARB) has shown declines in ambient PAH concentrations.[39] These reductions are likely due to the implementation of air quality regulations targeting motor vehicle emissions and agricultural burning.[39] In contrast, indoor concentrations of airborne PAHs during typical home occupancy remain poorly characterized, representing a critical gap in understanding exposure sources and pathways. This information is important for targeting effective interventions and reducing health disparities.

Biomonitoring offers a complementary approach for assessing exposure to airborne PAHs; however, PAH metabolites can also result from dietary sources, including consumption of foods that have been baked, toasted, grilled, fried, or smoked, as well as vegetables and fruits that are exposed to PAHs in the environment during production.[54] PAHs are metabolized by the cytochrome P-450 in the human body. They become hydroxylated in an effort to convert the lipid soluble compounds into water soluble metabolites that can be excreted in urine.[52] Mechanisms of mutagenicity and carcinogenicity are thought to be activated by the secondary metabolism of PAHs, including DNA adducts. PAHs are also documented as potent immune system suppressants, and there is evidence linking the metabolism of PAHs with immune system toxicity and oxidative stress .[52,55] Although the half-life of PAHs in the human body is relatively short (2-6 hours) the collection of urinary metabolites is relevant to contributing an understanding of the multiple sources of PAH exposure.[56,57]

In this study, we examine the relationship between indoor and outdoor airborne PAH concentrations in residential settings, assess the contribution of housing characteristics that may affect this relationship, investigate how indoor household activities and product use affect indoor airborne PAH concentrations, and describe the contribution of these indoor airborne PAH concentrations to urinary PAH metabolite concentrations.

2.2 Methods

2.2.1 Recruitment of Study Population

Eligibility criteria for recruitment included one adult and one child (3-13 years old) per residence who spoke either English or Spanish and lived in Stockton or Fresno, California. Participants were enrolled by community organizations in Stockton (Little Manila Rising) and Fresno (Central California Asthma Collaborative) through word of mouth and snowball recruitment.

Disadvantaged neighborhoods in these cities were targeted for recruitment to better understand air pollutant concentrations in impacted communities. There were 12 participating homes in Stockton and 52 in Fresno. Written informed consent was obtained from adults prior to their enrollment in the study, and children 7 to 13 years old provided their assent to participate. All study activities were approved by the Institutional Review Board (IRB) at the University of California, Berkeley (Protocol ID Number 2021-06-14436).

2.2.2 Air Sample Collection

Particle-bound and gaseous PAHs were collected on 37-millimeter quartz fiber filters (PallFlex Tissue Quartz) placed within Harvard Impactors. A pump calibrated to a flow rate of 10 liters per minute (LPM) pulled air through the Harvard Impactor sampling apparatus (Noth et al., 2011, 2016). Flow rates were assessed pre- and post-sampling using calibrated field rotameters. In preparation for sampling, quartz fiber filters were baked at 425 degrees Fahrenheit to remove contaminants and were then impregnated with a slurry of ground and cleaned XAD-4 resin in dichloromethane to collect PAHs that may partition into the gas-phase (Gundel et al., 1995; Lee et al., 2004). The Harvard Impactor inlet collected particulate matter with an aerodynamic diameter of 10 micrometers (PM_{10}) or smaller. NAP, which is entirely in the gas phase, was collected with XAD-containing sorbent tubes (SKC). Pumps pulled air through the sorbent tubes at a flow rate of 0.2 LPM for the 24-hour sampling duration according to previously reported method details.[47] Pumps were calibrated before and after sampling. Images of these sampling methods are provided in the supplemental materials (Fig. S1).

Air monitoring equipment was placed inside and outside of 64 participant homes for 24 hours, starting between 9:00 AM and 12:00 PM. One indoor and one outdoor sample were collected at each home between February and September of 2023. All samples were placed in coolers with ice-packs immediately after collection from participants' homes and during transport to the lab, where they were stored at -20°C.

Field blanks (n=20) and duplicates (n=13) for NAP comprised approximately 26% of total sorbent tube samples. Field blanks (n=11) and duplicate (n=9) for the remaining PAH compounds comprised approximately 16% of total filter samples. Lab blanks were used to perform lab quality control and compared to field blanks values to evaluate possible contamination.

2.2.3 Urine Sample Collection

HPLC-grade urine sample collection cups, small coolers, and icepacks were provided to participants during the setup of air sampling equipment at their residence. One adult and one child at participating homes were asked to provide a "first morning void" urine sample the following morning. This urine sample was designed to characterize exposure to PAHs during the same time period that air monitoring equipment was operating at the residence. First morning void urine samples were placed into provided coolers with ice packs after self-collection by participants. Study staff picked up the coolers and the air monitoring equipment, approximately 24 hours after setup.

Collected field blanks represented approximately 10% of the total urine samples collected in the study. Field blanks were prepared by placing 40 milliliters of HPLC-grade water into the urine collection cups and storing them in sterile bags in the freezer. Urine sample and field blanks were stored in the field freezer (- 80° C) until monthly transport on dry ice to the California Public Health Department Environmental Health Laboratory (CDPH EHL) in Richmond, CA where they were aliquoted and analyzed for specific gravity using a refractometer. The aliquots were stored in the lab freezer (- 80° C) until they were delivered to the Clinical Pharmacology Laboratory at the University of California, San Francisco for analysis of PAH metabolites.

2.2.4 Air PAH Sample Analysis

NAP, FLU, PHE, and PYR were analyzed as reported previously.[39] Briefly, FLU, PHE, and PYR collected via filter samples (n=121) were ultrasonically extracted in dichloromethane followed by vacuum filtration and then concentrated under nitrogen gas. NAP samples (n=123) were extracted from XAD sorbent tube media (SKC) into dichloromethane while shaking. Analyses to identify and quantify these compounds were performed by gas chromatography/mass spectrometry (GC/MS) (Agilent 7820/5977E) in the selected ion-monitoring mode with a 30m (5%-Phenyl)-methylpolysiloxane column (Agilent HP-5MS). Serial dilution concentrations of standards (SPEX CertiPrep and MilliporeSigma) were run with samples in the concentrations of 2, 5, 10, 25, 50, and 250 parts per billion. For each day of analysis and compound, we used separate standards and standard curves to establish a mass value via chromatographic peak integration. Sample results were blank-corrected by subtracting the average field blank value from each of the sample values. Mass values of PAH compounds derived from analysis were converted to mass concentrations in ng per cubic meter (ng/m^3) by dividing the blank-corrected mass by the volume of air sampled for each sample.

Limits of detection (LOD) for NAP (5.79 ng), FLU (44.29 ng), PHE (77.33 ng), and PYR (55.14 ng) were derived by combining the average of field blanks plus two standard deviations. Values below the LOD (< LOD) were imputed by dividing the LOD value by the square root of two, a method appropriate for logarithmically distributed data.[58] One field blank was excluded from the average of the field blanks for NAP, FLU and PHE because it was higher than the 95^{th} percentile of the field blanks. NAP duplicate sample pairs showed a mean coefficient of variation (i.e., the standard deviation divided by the mean) of 22%. Filter duplicate sample pairs showed mean coefficients of variation of 30% for FLU, 50% for PHE and 40% for PYR.

2.2.5 Urinary Metabolite Analysis

A total of 128 urine samples from adult and child participants were analyzed by the Clinical Pharmacology Laboratory at the University of California, San Francisco (UCSF CPL). Urine samples were treated with beta-glucuronidase to hydrolyze conjugates and release free hydroxy metabolites of four PAH compounds (naphthalene, fluorene, phenanthrene, and pyrene).[59] PAH metabolites were then extracted with HPLC grade pentane and ethyl acetate (Fisher Scientific) and converted to pentafluorobenzyl derivatives to enhance detection sensitivity.

Extracts containing these derivatives were injected into the Liquid Chromatography Mass Spectrometry (LC/MS) (Surveyor HPLC interfaced to a TSQ Quantum Ultra triple-stage quadrupole mass spectrometer (Thermo-Finnigan)), which was used to quantify PHE, FLU, and PYR metabolites individually. Due to co-elution from the LC column (a PAH Green column (4.6 × 150 mm, Thermo-Hypersil-Keystone (Bellefonte)), the two urinary metabolites of naphthalene (1-naphthol and 2-naphthol) were reported together as a single value (naphthols).[56]

The limits of quantification (LOQ) for these compounds were: 0.025 ng/mL for 1-hydroxyfluorene (1-FLU), 2- hydroxyfluorene (2-FLU), 3- hydroxyfluorene (3-FLU), 1-hydroxyphenanthrene (1-PHE), 2- hydroxyphenanthrene (2-PHE), and, 1-hydroxypyrene (1-PYR); 0.05 ng/mL for 3,4- hydroxyphenanthrene; and 0.25 ng/mL for naphthols.

In a separate analysis, urinary 1-naphthol (1-NAP) and 2-naphthol (2-NAP) were analyzed in 118 samples using Gas Chromatography Mass Spectrometer (GC/MS) (a Thermo Trace 2000 GC with a 0.25 mm i.d. × 25 m DB-5 column (J & W Scientific) interfaced to a Finnigan TSQ 7000 mass spectrometer). The LOQ was 0.25 ng/mL for 1-NAP and 2-NAP. UCSF CPL also measured nicotine metabolites, cotinine (COT) (LOQ = 0.05 ng/mL) and trans-3'-hydroxycotinine (3HC) (LOQ = 0.1 ng/mL) via LC/MS as previously reported.[60]

Urinary metabolite concentrations vary by individual hydration status; therefore, all metabolite values were normalized by specific gravity.[61] Specific gravity was measured by the CDPH EHL. Urinary metabolite values were adjusted for specific gravity based on the ratio of the specific gravity reference value to participants' specific gravity measurements from each urine collection as previously reported.[48,62] (See supplemental information). The reference value of 1.018 corresponds to the median value reported in the National Health and Nutrition Examination Survey (NHANES) 2007-2008 survey cycle among 6544 male and female participants age 6 and older.[63]

2.2.6 Questionnaire Data & Covariates

Participant information and housing characteristics were collected through questionnaires administered during both the setup and removal of air monitoring equipment at each residence. Participants were asked to complete an activity log detailing their household activities during the 24-hour air sampling period. Estimates of traffic proximity to each participating home in the study were obtained from Tracking California, which combined daily vehicle miles traveled and annual vehicle miles traveled from 2019 into a traffic tool.[64] Distance of participant homes from Highway 99 was also measured in kilometers and included in the data set as a continuous variable. Information on the year each home was built and its square footage was sourced from publicly available data (Zillow).[65]

Meteorological data for 2023, including daily average temperature, wind speed, daily average relative humidity, and total liquid content (as a measure of precipitation), were downloaded from the National Oceanic and Atmospheric Administration (NOAA) website. Measurements were taken from the Stockton Airport and Fresno International Airport monitoring stations.[66]

2.2.7 Data Analysis

Summary statistics were calculated for airborne PAH and urinary metabolite concentrations. Values below the limit of detection (LOD) were imputed as the LOD divided by the square root of two.[67,68] Non-parametric comparisons of paired data were conducted using Wilcoxon Signed Rank tests. Bivariate ($log(Y_i) = \beta_0 + \beta_1 X_1 + \varepsilon$) and multivariate ($log(Y_i) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \varepsilon$) log-linear regression models, Pearson's correlation using logtransformed data, and Wilcoxon Signed-Rank and Analysis of Variance (ANOVA) tests were used to investigate relationships within the data. Assumptions of linearity and independence were evaluated using residual plots and Q-Q plots. Because airborne PAH concentrations were log-normally distributed, values were log-transformed (natural log) to normalize the skewed distributions prior to linear regression modeling. Model selection was guided by comparisons of Akaike Information Criterion (AIC) values and evaluated using ANOVA-based omnibus test to assess model goodness of fit. All statistical analyses were completed using R (version 4.2.1).[69]

2.3 Results

Participant demographics and home information can be found in **Table 1**. Almost half of the participants in this study identify as Hispanic or Latino/a, with approximately half of participants reporting Spanish as their primary language and half reporting English. More than half of participants also reported an annual household income of $30,000 or less. There were no differences in indoor or outdoor PAH air concentrations by demographic characteristics.

Table 1: Participant Demographics and Home Information

Language Spoken	English	33 (52%)
	Spanish	31 (48%)
Age of Child Participants (Mean ± SD)		8.84±2.6
Age of Adult Participants (Mean ± SD)		41.89±7.58
Gender of Adult Participants	Male	2 (3%)
	Female	62 (97%)
Gender of Child Participants	Male	33 (52%)
	Female	29 (45%)
	Non-binary	2 (3%)
Race/Ethnicity	Hispanic/Latino	46 (70%)
	White	8 (12%)
	Black/African American	3 (5%)
	Asian	2 (3%)
	Multiple Races/Ethnicities	7 (10%)
Household annual Income	less than $15,000	11 (17%)
	$15,000 to $30,000	25 (39%)
	$30,000 to $50,000	9 (14%)
	$50,000 to $75,000	4 (6%)
	More than $75,000	15 (23%)
Educational Attainment	College graduate or above	18 (28%)
	Some college or AA degree	15 (23%)
	High school graduate, GED, or equivalent	8 (13%)
	Some high school	5 (8%)
	2nd through 9th grade	18 (28%)
Rent or Own Home	Rent	35 (55%)
	Own	29 (45%)
Type of Home	Mobile home	3 (5%)
	Single family detached home	44 (69%)
	Residential duplex	3 (5%)
	Apartment building	14 (21%)
Square Footage of Home	300 - 900	14 (23%)
	900 - 1600	24 (39%)
	1600 - 2300	15 (24%)
	2300 - 4000	8 (13%)

Some analyses of PYR were not quantifiable due to GC/MS error, and as a result, PYR measurements from 51 samples were not reported. One outdoor filter sample and two indoor filter samples (PYR, FLU, and PHE), and one outdoor sorbent tube sample and three indoor sorbent tube samples (NAP) were invalidated due to participants requesting to turn off sampling equipment due to noise, error during transfer of sorbent tube media to extraction vial, or errors during field collection including post-sampling calibration, filter placement, and securing tube connections in air monitoring equipment. A total of 104 NAP samples, 117 PHE and FLU samples, and 66 PYR samples were analyzed. Duplicate samples were averaged and reported as one sample during data analysis, therefore the dataset included 110 NAP samples, 108 FLU and PHE samples, and 62 PYR samples.

2.3.1 Indoor and Outdoor concentrations in Stockton and Fresno and Seasonal Variability

NAP was detected in 58% of indoor samples and 33% of outdoor samples, FLU was detected in 5% of indoor samples and 10% of outdoor samples, PHE was detected in 18% of indoor samples and 20% of outdoor samples, and PYR was detected in 16% of indoor and 20% of outdoor samples (**Table 2).**

Figure 2. Indoor and Outdoor NAP Concentrations

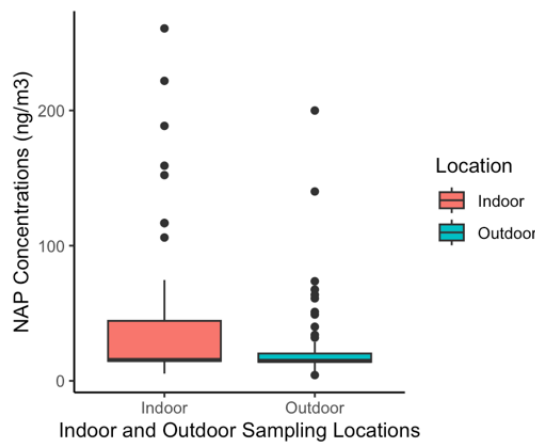

Figure 2. *Detected and imputed indoor and outdoor NAP values are shown.*

The average indoor-to-outdoor (I/O) ratios for FLU, PHE and PYR were all close to 1 (range = 0.99 – 1.2); however, indoor concentrations were significantly higher than outdoor concentrations for NAP (**Figure 2**). The median NAP concentration of indoor and outdoor samples above the LOD were 49 ng/m^3 and 44 ng/m^3, respectively, and the I/O ratio of samples above the LOD was 2.3. After imputation for samples below the LOD, indoor and outdoor NAP medians were 16 ng/m^3 and 15 ng/m^3, respectively, and mean I/O ratio was 1.9. Geometric means and arithmetic means of samples above the LOD can be found in the Supplemental Information.

Table 2: Summary of Indoor and Outdoor PAH Air Concentrations (ng/m3) Collected from Homes^*~

		NAP n=110	FLU n=108	PHE n=108	PYR n=62**
Indoors	Minimum	5	2	3	3
	25th Percentile	15	2	4	3
	Median	16	2	4	3
	75th Percentile	58	2	4	3
	95th Percentile	164	3	9	7
	Maximum	261	4	11	9
	Detection Frequency	58%	5%	18%	16%
Outdoors	Minimum	5	1	2	2
	25th Percentile	14	2	4	3
	Median	15	2	4	3
	75th Percentile	26	2	4	3
	95th Percentile	71	4	9	5
	Maximum	200	8	9	9
	Detection Frequency	33%	10%	20%	20%
Indoor-to-Outdoor Ratio		1.9	0.99	1.0	1.2

^ Limits of Detection (LODs): NAP = 5.79 ng; FLU = 44.29 ng; PHE = 77.33 ng; and PYR = 55.14 ng
Values below the LOD have been imputed by dividing the LOD by the square root of 2
*Duplicate sample concentrations were averaged, and are not reflected in the total sample size
For NAP samples n= 59 indoor, 51 outdoor; FLU and PHE samples n= 57 indoor, 51 outdoor, and PYR samples n= 32 indoor, 30 outdoor
~ Indoor-to-outdoor ratios reported here were are arithmetic means of each indoor to outdoor ratios from participants' homes, which included detected and imputed values among indoor-outdoor matched pairs
**Instrument error resulted in fewer quantifiable PYR samples than other PAHs

Higher concentrations of indoor and outdoor NAP were observed at Stockton homes (n= 10) as compared to Fresno homes (n=54) **(Figure 3),** which were significantly different based on Wilcoxon Signed-Rank Tests (p-values < 0.05). Fifty percent of Stockton samples were collected in the spring and 50% were collected in the summer, whereas Fresno samples were collected across spring, summer and fall seasons. Other PAHs did not differ by city. Because of the small number of Stockton homes, we have accounted for city as a fixed effect in subsequent analyses.

Figure 3. Indoor & Outdoor NAP Concentrations by City

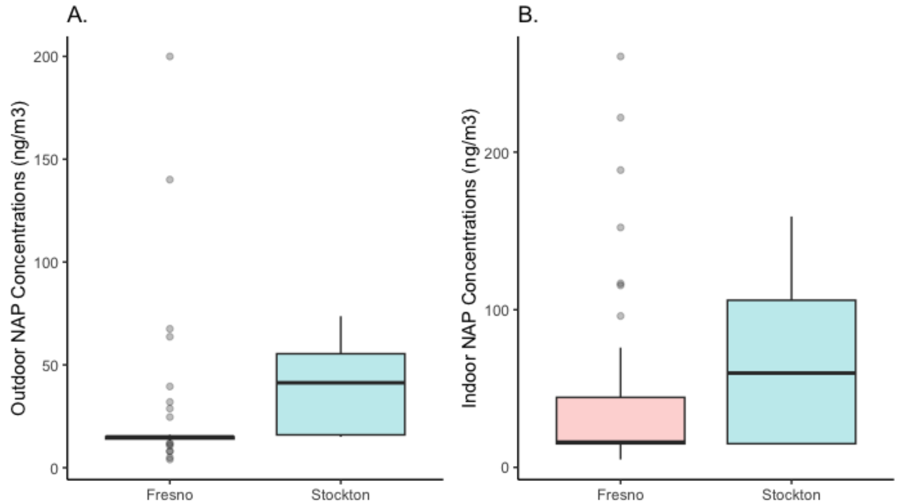

Figure 3. A. Outdoor NAP concentrations by city. B. Indoor NAP Concentrations by city.

Indoor and outdoor measurements of airborne NAP, FLU and PHE, respectively, were significantly correlated with each other. (Results can be found in Table S2 in the Supplementary Information). Indoor and outdoor PYR concentrations were weakly correlated, albeit not significantly. Log linear regression models reveal that outdoor concentrations were significantly associated with indoor concentrations for NAP, FLU and PHE, respectively (p-values < 0.05) **(Figure 4).**

Figure 4. Relationships between indoor and outdoor PAH air concentrations

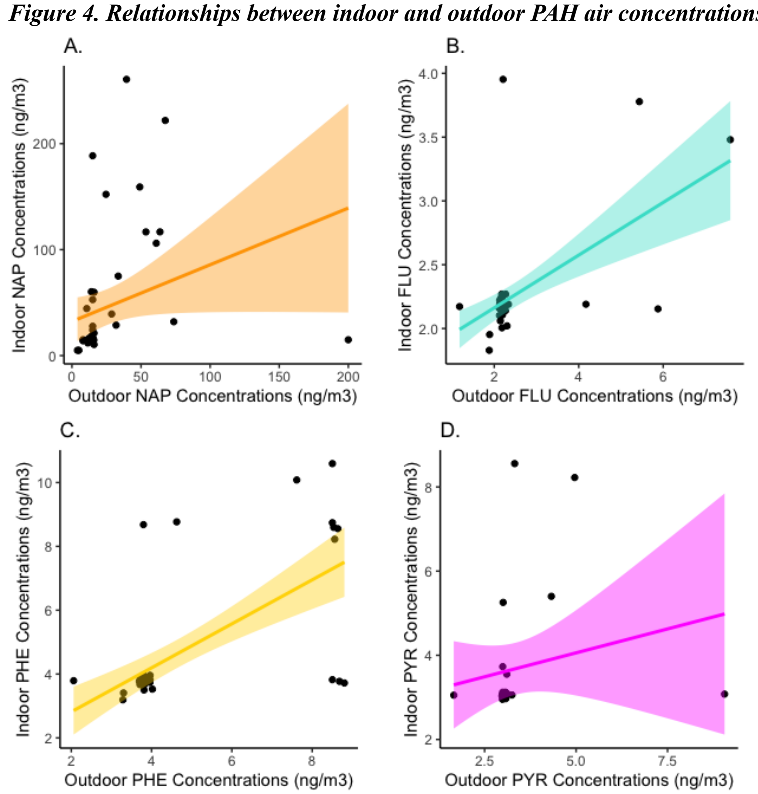

Figure 4. Untransformed indoor and outdoor PAH correlations (linear regression formula: Yi = ß0 + ß1X1 + ε) displayed with a 1:1 aspect ratio. A. NAP concentrations. B. FLU concentrations. C. PHE concentrations. D. PYR concentrations.

Outdoor concentrations of all four PAHs were weakly to moderately correlated with each other (p-values < 0.05). Similarly, indoor concentrations of all four PAHs were weakly to moderately correlated with each with other (p-values < 0.05). NAP, however, was not correlated with summed PHE, FLU and PYR.

Season (analyzed as a categoricial variable) was significantly associated with NAP, FLU and PHE concentrations in bivariate and multivariate regression models, indicating seasonal differences in PAH concentrations. Spring concentrations were significantly higher than summer and fall concentrations for NAP, and Spring concentrations for FLU, PHE, and PYR were significantly higher than fall concentrations (p-value < 0.05) **(Figure 5).** These associations were seen when looking at PAH concentrations across Fresno and Stockton. Similar differences by season were observed within the city of Fresno as well; NAP, FLU and PHE had significantly different means (p-value < 0.05) by season, with higher concentrations observed in the spring.

Figure 5. PAH Air Concentrations by Season

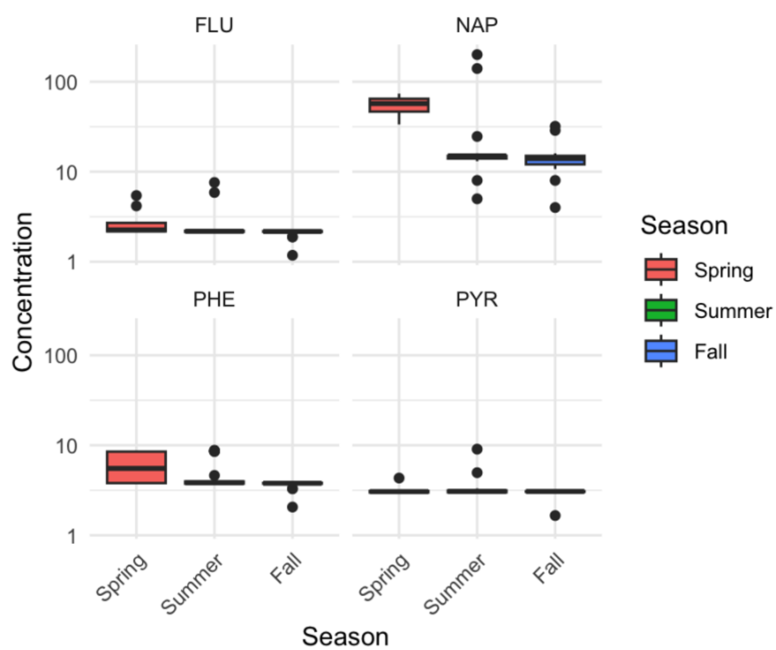

Figure 5. Concentrations of FLU, NAP, PHE, and PYR (ng/m3) by season.

Associations between air PAH concentrations and continuous meterological variables (i.e. daily average temperature (°C), daily average wind speed (m/s), daily average relative humidity (%), and total liquid content (mm/day, as a measure of precipitation)), were evaluated using log-linear regression **(Table 3)**. Temperature, wind speed, relative humidity and precipitation were significantly associated with indoor NAP in bivariate relationships, and when outdoor NAP and season were added to the model, only wind remained significant. Temperature was significantly associated with indoor FLU and stayed significant after outdoor FLU and season were added to the multivariate model. Temperature and precipitation were significantly associated with indoor PHE in bivariate relationships, but became insignificant when outdoor PHE and season was added. Season, wind speed, and temperature were accounted for in subsequent analyses when these variables illustrated explanatory power. PYR is not included in **Table 3** because there were no significant relationships observed in bivariate regressions with these seasonal and meterological variables.

Table 3. Bivariate regression analyses summary of how seasonal and meteorological variables affect the relationship between indoor and outdoor PAH air concentrations ($Y_i = \beta_0 + \beta_1 X_1$)

PAH	Outcome Variable	Treatment Variable(s)	Estimate	Confidence Interval	p-value
NAP	Indoor	Outdoor	0.806	(0.485, 1.12)	6.69E-06
	Indoor	Season (Spring)	1.58	(1.09, 2.06)	2.40E-08
	Indoor	Temperature	-0.0421	(-0.0628, -0.0213)	0.00015
	Indoor	Wind Speed	0.17966	(0.0763, 0.282)	0.000959
	Indoor	Relative Humidity	0.02088	(0.000703, 0.0410)	0.0428
	Indoor	Precipitation	2.9359	(-0.243, 6.11)	0.0696
FLU	Indoor	Outdoor	0.26838	(0.152, 0.383)	2.39E-05
	Indoor	Season (Spring)	0.13169	(0.0345, 0.228)	0.00883
	Indoor	Temperature	-0.003609	(-0.00700, -0.000217)	0.0374
	Indoor	Wind Speed	0.009396	(-0.00616, 0.0249)	0.232
	Indoor	Relative Humidity	0.001347	(-0.00177, 0.00446)	0.391
	Indoor	Precipitation	0.23936	(-0.3908, 0.869)	0.45
PHE	Indoor	Outdoor	0.7348	(0.526, 0.942)	4.64E-09
	Indoor	Season (Spring)	0.43497	(0.216, 0.652)	1.94E-04
	Indoor	Temperature	-0.010427	(-0.0188, -0.00199)	0.0163
	Indoor	Wind Speed	0.0322	(-0.00655, 0.0709)	0.102
	Indoor	Relative Humidity	0.004864	(-0.00294, 0.0126)	0.217
	Indoor	Precipitation	2.04934	(0.579, 3.51)	0.00716

2.3.2 Structural and Place-Based Characteristics of Homes and the Relationship Between Indoor and Outdoor Concentrations and Infiltration

There is evidence of infiltration of outdoor PAHs into the home environment. We investigated the effect of the following household characteristics on the relationship between indoor and outdoor PAHs: type of home, age of home, square footage of home, traffic proximity, and the presence of double-paned windows, weatherstripping around doors, and weatherstripping around windows. We were not able to identify any factors in our data set that have moderating effects on the indoor-outdoor relationship or infiltration rates.

Traffic volume and proximity (measured as daily and annual vehicle-miles traveled within 100-1000 km of residences) was associated with neither indoor nor outdoor concentrations for NAP, PHE, and PYR. However, both indoor and outdoor concentrations of FLU concentrations were significantly associated with annual vehicle miles traveled within 250 meters of residences **(Figure 6).** After accounting for outdoor FLU, season, and wind, traffic volume near the home remained a significant predictor of indoor FLU concentrations (p-value < 0.05). Participant home proximity to highway 99 (in km) was not associated with indoor or outdoor PAH air concentrations.

We evaluated the effect of home type on indoor PAH in bivariate and multivariate linear regression models. After accounting for outdoor NAP, season, and wind speed, living in mobile homes (n=3) was significantly associated with higher indoor NAP concentrations (p-value < 0.05). This suggests that the expected indoor NAP concentrations were 9.9 times higher in mobile homes compared to residential duplexes. Most participants lived in single family homes, which had lower concentrations among all four measured PAH compounds as compared to other home types. Only three participants lived in mobile homes, and three participants lived in residential duplexes **(Table 1).**

Figure 7 compares airborne PHE and NAP concentrations by home type. Outdoor concentrations of NAP and PHE were significantly higher among residential duplexes and mobile homes than other types of homes.

Figure 6. Traffic Volume and Outdoor FLU Concentrations

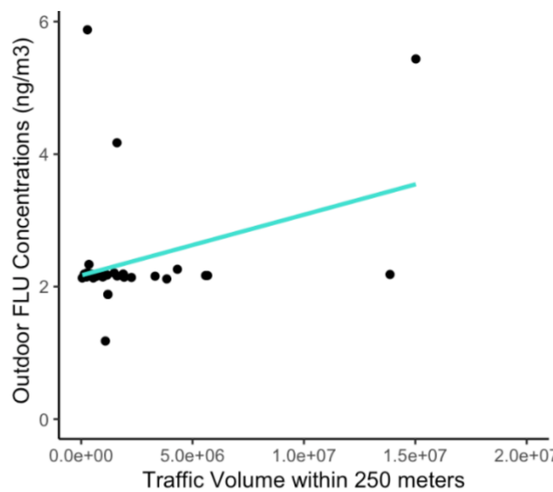

Figure 6. Correlation between untransformed outdoor FLU concentrations and traffic volume (annual vehicle miles traveled within 250 meters of residences) (linear regression formula: Yi = ß0 + ß1X1 + ε).

Figure 7. Outdoor PHE and NAP Air Concentrations by Home Type

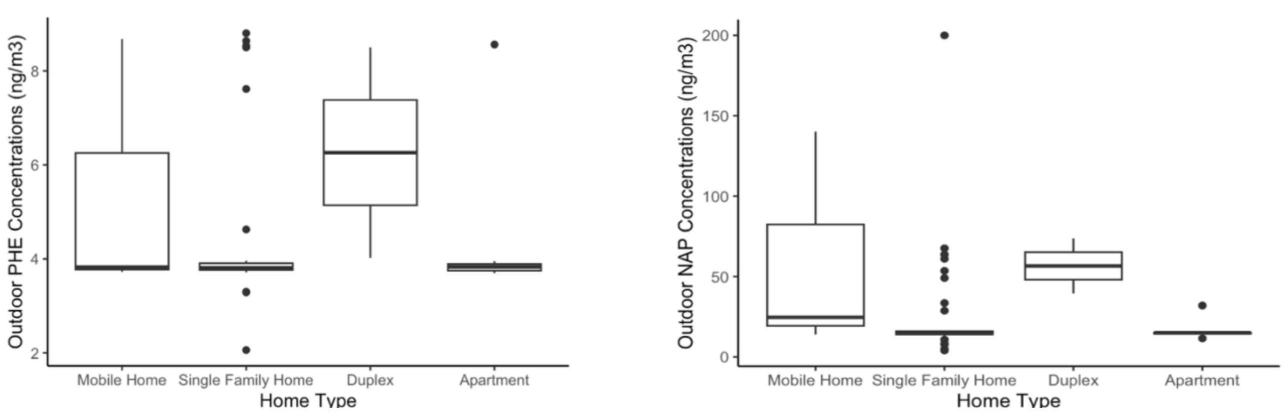

Figure 7. Outdoor PHE concentrations by home type and outdoor NAP concentrations by home type

We did not find an association between indoor concentrations and the presence of weatherstripping around doors or windows**.** Although having double paned windows and owning the home were significantly associated with indoor concentrations in bivariate relationships, when controlling for outdoor concentrations, wind speed and season, these factors were no longer significant. Size and age of homes, included as continuous variables, were also not significantly associated with indoor concentrations.

Thirty-four study participants lived in a home that they rented and 29 were home owners. Owners had significantly higher airborne PAH concentrations than renters: indoor NAP was significantly higher, outdoor NAP was higher, but not significant, indoor and outdoor FLU were significantly higher, outdoor PHE was significantly higher, and indoor PHE was higher, but not significant. Housing characteristics between participating households may influence these results **(Table 4).**

Table 4. Housing Characteristics among Home Owners and Renters

	Housing Characteristics	**Owners**	**Renters**
Stove Type	Only had gas stove in the house	20 (32%)	21 (33%)
	Only had an electric stove in the house	9 (14%)	11 (17%)
Attached Garage	Regularly parked in an attached garage	20 (32%)	4 (6%)
Highway Proximity	Lived within 5 km of Highway 99	16 (25%)	17 (27%)
Home Type	Lived in single family home	26 (41%)	18 (29%)
	Lived in mobile home	2 (3%)	1 (2%)
	Lived in apartment	0 (0%)	13 (21%)
	Lived in duplex	1 (2%)	2 (3%)
	Total	29	34

Among the owners, 69% of them (20) also regularly parked in an attached garage, however only 4 renters regularly parked in attached garages. Participants with attached garages had significantly higher indoor FLU, higher but not significant outdoor FLU and indoor NAP. Eight owners either did not have an attached garage or did not regularly park in their attached garage. Sixty eight percent of renters lived within 3 km of Highway 99 (within approximately the 25^{th} percentile of households living closest to the highway), whereas fewer owners (31%) lived within 3 km. Households within 3 km of Highway 99 were 13 single family homes, 5 apartments, and one residential duplex.

2.3.3 Home Activities, Product Use and Indoor PAH Concentrations

Cooking

Sixty three percent of participants reported having a gas stove, 33% reported having an electric stove, and 3% reported having half gas and half electric. Although not statistically significant, homes with gas stoves generally had higher indoor NAP concentrations than homes with electric stoves. While median concentrations were similar, elevated outlier values for indoor NAP, FLU, PHE and PYR were observed in homes using gas stoves. This was consistent with linear regression results, which showed that participants who used electric stoves during the sampling period had regression coefficients an order of magnitude lower than those who used gas stoves, after adjusting for outdoor PAH concentrations and season. Similarly, participants who reported any oven use during the 24-hour sampling period had higher indoor NAP concentrations, although this difference was also not statistically significant. Questionnaires did not ask whether participants had gas or electric ovens. We did not detect differences between participants that used their stove or barbeque and those who did not use a stove or barbeque during the study period.

Heating & Appliances

No participants reported using a wood-burning stove during the study period. One household used a gas-powered floor or wall heater during the study period. Fifty-eight (91%) of participants reported not using the heat during the study period; the 6 participants that did use heat all used a gas-powered furnace or central heat system. A Wilcoxon Rank-Sum test shows that indoor NAP, FLU, and PHE concentrations among participants that used gas-powered heat in their homes during the study period were significantly different from participants that did not heat their homes. In linear regression models, using gas-powered heat was significantly associated with indoor concentrations of FLU (p-value < 0.001) and PHE (p-value < 0.001) while controlling for outdoor concentrations and season **(Figure 8)**. NAP was significantly associated with gas-powered heat use in a bivariate relationship, but became insignificant when adjusting for outdoor NAP concentration and season. Having a gas-powered dryer or hot water heater in the home was not associated with indoor PAH concentrations.

Figure 8. Indoor NAP, FLU and PHE Concentrations and Gas-Powered Heating of the Home

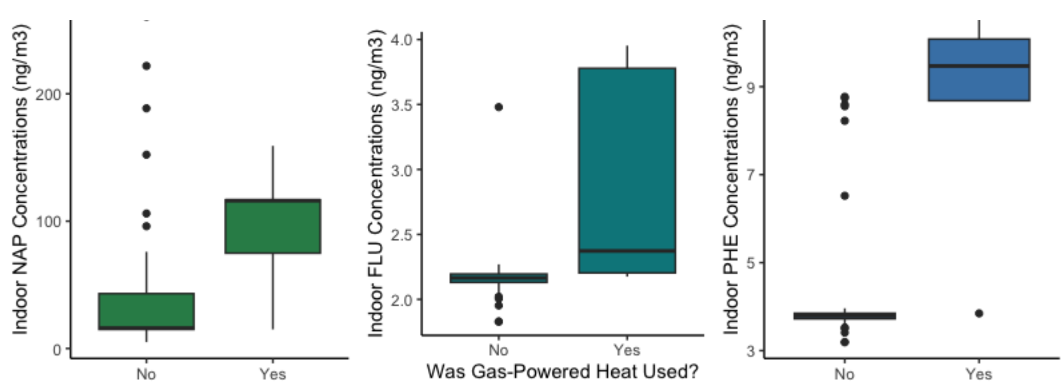

Figure 8. Indoor NAP, FLU, and PHE Concentrations displayed among participants that did and did not use gas-powered heat during the study period.

Smoking/Vaping

One participant reported vaping or smoking cannabis in their home during the study period. Three other participants reported that someone vaped or smoked in their home during the study period between one and three times. Among two of these homes, participants reported that vaping occurs inside the home every day on average. We did not find evidence of significant differences between homes where smoking/vaping occurred and where it did not occur.

Candles and Incense

Eight participants reported burning candles in their home between 1-4 times during the 24-hour sample collection period. Burning candles in the home during the study period was significantly associated with higher indoor PYR concentrations, which was still significant after controlling for season and outdoor PYR concentrations. The second highest indoor PYR concentration measured in this study was measured in the home where candles were burned 4 times during the 24-hours study period.

Two participants reported burning incense 1-2 times during the study period. We did not detect a relationship between indoor PAH concentrations and burning incense. The participant that smoked cannabis in the home also reported burning incense in the home two times during the study period.

Ventilation and Air Filtration

Eighteen percent of participants reported not opening windows during the 24-hour sample collection period. Twenty-six percent reported opening windows 1 or 2 times. Fifty-three percent of participants reported opening windows 3 to 5 times during the sampling period. Participants who opened windows 3 or more times had indoor NAP concentrations 1.8 times higher than participants who opened windows less than 3 times during the sampling period. After accounting for season and wind speed, home type, presence of double-paned windows, and frequency of open windows (as a continuous variable) explained 52% of the variability in indoor NAP concentrations **(Figure 9).**

Figure 9. Frequency of Open Windows and Indoor NAP Concentrations

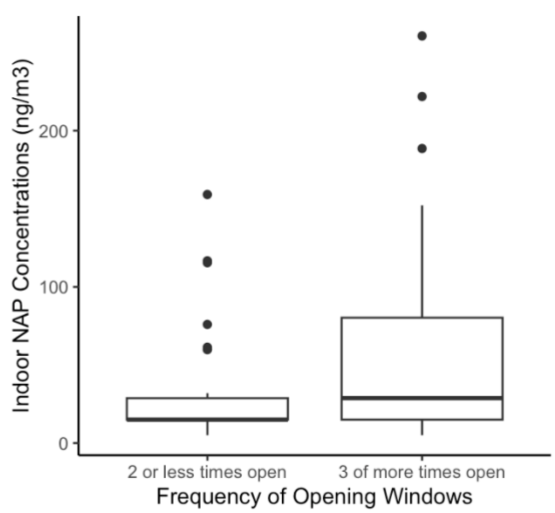

Figure 9. Indoor NAP concentrations are displayed by self-reported frequency of opening windows during the study period (opening windows 2 times or less or opening windows 3 times or more)

Although these variables were not significant, this finding points to the impact of opening windows on infiltration of outdoor PAHs.

Temperature, season, traffic volume, age of home, and outdoor FLU concentrations were significant predictors of indoor FLU concentrations, accounting for 57% of the variability of indoor FLU concentrations. No covariates added additional explanatory power to the relationships between indoor and outdoor PHE and indoor and outdoor PYR.

Nine participants reported that they typically use their portable air filter every day, or nearly every day, however only six participants reported using a portable air filter in their home during the study period. The airborne PAH concentrations in these homes were not statistically different from homes that did not use air filtration. Additionally, one of the homes that used a portable air filter also reported opening windows, which can allow for infiltration of outdoor air pollutants.

Forty-four participants reported that they used their exhaust hood or vent fan between one and 7 times while cooking during the study period, which is consistent with the fact that 37 participants (57%) expressed before the sampling began that they use their exhaust hood every time they cook, and 34% reported that they sometimes use it when they cook. We did not detect a relationship between use of the exhaust hood and airborne PAH concentrations.

Product Use in the home

Indoor FLU concentrations were significantly higher in homes where residents regularly parked their vehicle in an attached garage (n=24) compared to other homes (including homes without an attached garage) (Wilcoxon Rank-Sum p-value <0.05). Additionally, log-transformed indoor FLU concentrations were significantly associated with regularly using the attached garage after controlling for outdoor FLU concentrations and season. We did not find associations with other PAH compounds.

Figure 10. Indoor FLU Concentrations and Attached Garages

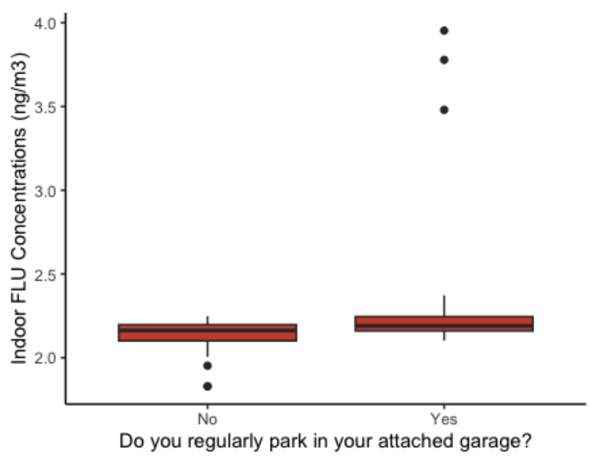

Figure 10. *Indoor FLU concentrations by the regular use of parking a vehicle in their attached garage. This did not necessarily represent participants who parked in an attached garage during the study period.*

Questionnaires were also used to ask participants if they used products inside the home during the study period, including if they had new construction, paint, caulking, sealant or furniture in their home in the last 6 months, if they store home repair products in the home, of if they used home repair products, air fresheners, pesticides, cleaning products (floor cleaner, glass cleaner, all-purpose cleaner, carpet cleaner, disinfectant wipes, restroom cleaner bleach, and furniture polish), or personal care products (shampoo, deodorant, perfume, scented body lotion, scented body wash, nail polish, nail polish remover). We did not detect associations between any of these variables and indoor PAH concentrations with the exception of floor cleaner. After accounting for season, wind, and outdoor PYR concentrations, the use of floor cleaner was statistically associated with increased indoor PYR concentrations. Bivariate relationships (coefficients and 95% Confidence Intervals) discussed in Section 3.3 are illustrated in **Figure 11.**

Figure 11. Bivariate Relationships of Indoor PAH Concentration by Possible Indoor PAH Sources

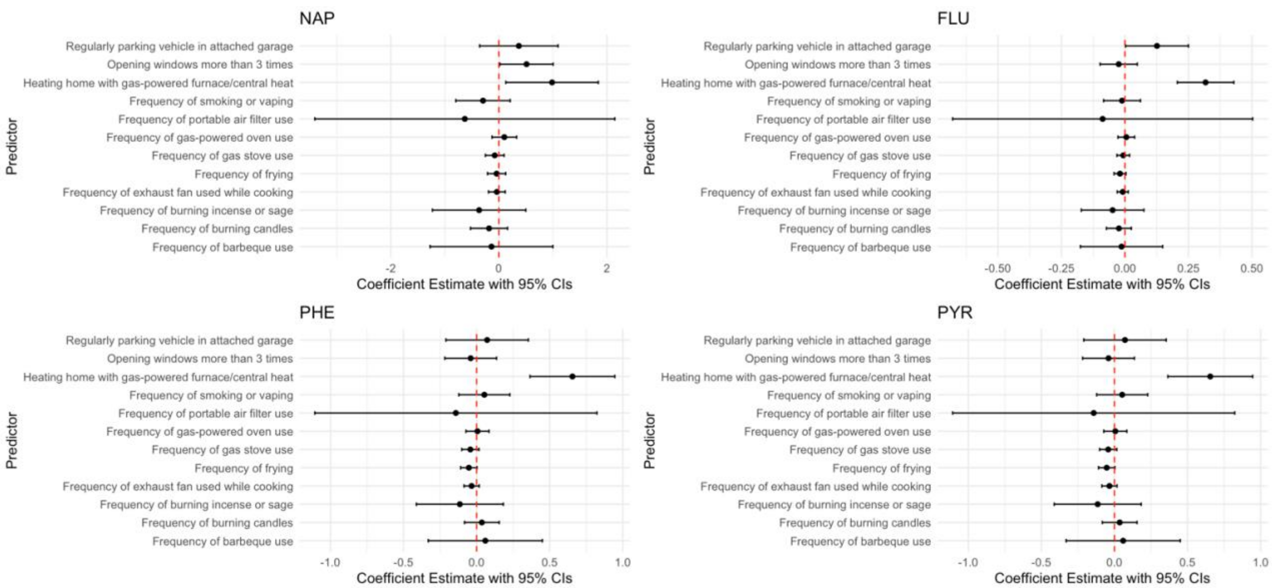

Figure 11. *Forest plot displaying bivariate relationships between log-transformed PAH concentrations and self-reported participant activities (regression formula: $Y_i = \beta_0 + \beta_1 X_1 + \varepsilon$). Participant activities included here are those thought to contribute to indoor PAH pollution. Coefficient estimates and 95% confidence intervals are shown on the x-axis.*

2.3.4 Urinary PAH Metabolites and Airborne PAH Concentrations

Urinary PAH metabolite concentrations are presented in **Table 5**. Metabolite concentrations among children were not statistically different from concentrations among adults. Values of summary naphthols measured by LC/MS were correlated with 1-NAP and 2-NAP measured independently by GC/MS. Urinary PAH metabolite concentrations were not associated with indoor or outdoor airborne PAH concentrations. Graphs showing relationships between indoor PAH concentrations and the summed value of all the corresponding PAH urinary metabolites is presented in **Figure 12.** Graphs showing the relationships between airborne NAP concentrations and urinary 1-NAP, 2-NAP, summed 1-NAP and 2-NAP and summed (co-eluded) naphthols are presented in the Supplemental Information. Because NAP and the insecticide carbaryl can devolve to urinary 1-NAP, we calculated the ratio of 1-NAP to 2-NAP to investigate possible sources of exposure. Naphthalene, but not carbaryl, also metabolizes to 2-NAP, therefore, the ratio of urinary 1-NAP to 2-NAP within an individual can provide information about the source of 1-naphthol. Based on previous studies, we can assume that a ratio > 2 indicates carbaryl as the source of 1-NAP.[70] Urinary 1-NAP concentrations were significantly lower than 2-NAP in this study, with an average ratio of 1-NAP to 2-NAP of 0.05.

Table 5. Summary of Urinary Metabolites of Polycyclic Aromatic Hydrocarbons among all participants (ng/mL)*^

	Minimum	Arithmetic Mean (Median)	Standard Deviation	75th Percentile	Maximum	% detected	Child/Adult Ratio Range	Child/Adult Ratio Median (Arithmetic Mean)
1-NAP	0.02	0.56 (0.20)	1.31	0.49	12.77	51%	0.0043 - 206	1.00 (8.70)
2-NAP	0.58	27.46 (14.55)	33.49	32.43	164.61	100%	0.23 - 4.9	0.71 (1.16)
naphthols	0.53	29.49 (17.67)	32.34	38.23	161.34	100%	0.25 - 6.6	0.80 (1.36)
1-FLU	0.01	0.06 (0.02)	0.14	0.04	0.99	57%	0.019 - 38.9	1.00 (1.82)
2-FLU	0.02	0.17 (0.10)	0.24	0.16	1.71	94%	0.045 - 6.74	0.83 (1.40)
3-FLU	0.01	0.06 (0.02)	0.13	0.04	1.32	54%	0.013 - 29.8	1.00 (1.54)
1-PHE	0.02	0.11 (0.06)	0.21	0.11	2.22	85%	0.017 - 19.2	0.92 (1.52)
2-PHE	0.02	0.07 (0.04)	0.10	0.08	0.89	67%	0.047 - 21.2	1.00 (1.86)
3,4-PHE	0.03	0.11 (0.06)	0.19	0.11	1.74	63%	0.081 - 37.8	1.00 (2.15)
1-PYR	0.02	0.12 (0.07)	0.17	0.14	1.90	89%	0.045 - 26.6	1.00 (2.25)

*Values are adjusted for specific gravity
^Limits of Quantification (LOQ): 1-naphthol = 0.25 ng; 2-naphthol = 0.25 ng; 1-hydroxyfluorene = 0.025 ng; 2-hydroxyfluorene = 0.025 ng; 3-hydroxyfluorene = 0.025 ng; 1-hydroxyphenanthrene = 0.025 ng; 2-hydroxyphenanthrene = 0.025 ng; 3,4-hydroxyphenanthrene = 0.05 ng; 1-hydroxypyrene = 0.025 ng

Figure 12. Relationship between Indoor Airborne PAH Concentrations and Urinary PAH Metabolite Concentrations

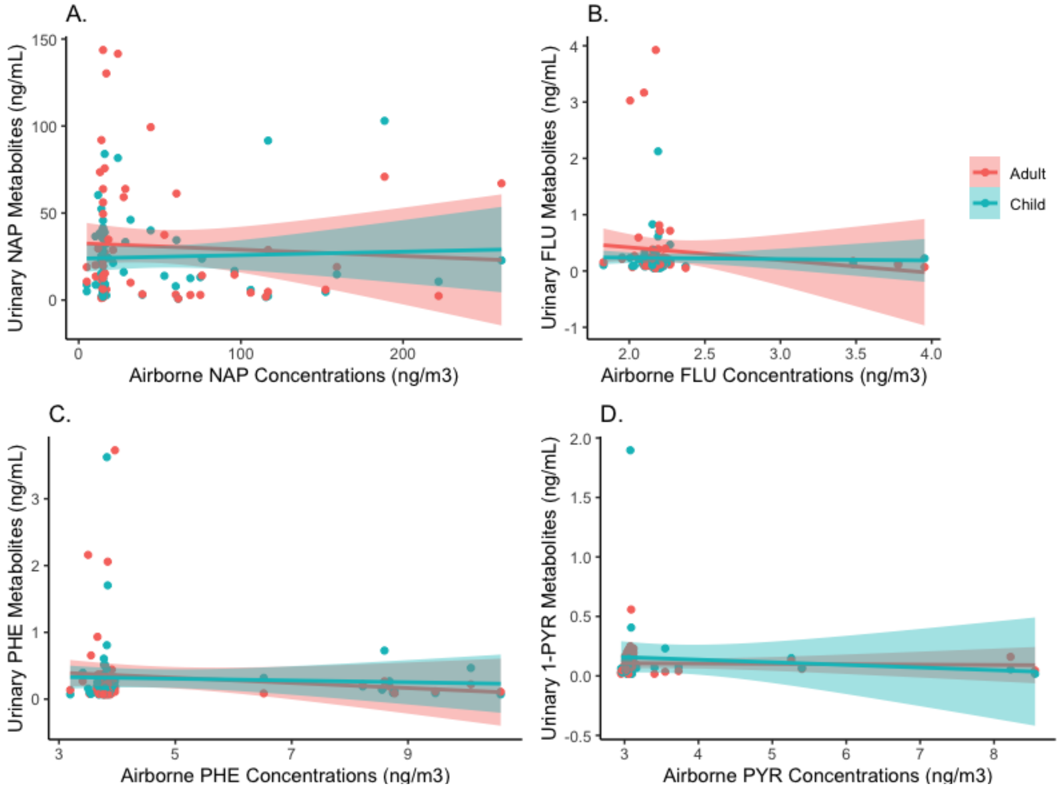

Figure 12. *Relationships between untransformed indoor airborne PAH concentrations (ng/m^3) and urinary PAH metabolite concentrations (ng/mL). Adults and child values are shown separately and with separate regression lines (regression line formula: $Y_i = \beta_0 + \beta_1 X_1 + \varepsilon$). For PAH compounds with multiple metabolite compounds measured (NAP, FLU, and PHE), respective metabolite compounds for each PAH were summed to represent values displayed in plots. A. NAP air concentrations and urinary metabolite concentrations. B. FLU air concentrations and urinary metabolite concentrations. C. PHE air concentrations and urinary metabolite concentrations. D. PYR air concentrations and urinary metabolite concentrations.*

Table 6. Specific Gravity-Adjusted Urinary Metabolites of Polycyclic Aromatic Compounds among Adults and Children Separately (ng/mL)

		Minimum (Median)	Arithmetic Mean	Standard Deviation	Geometric Mean	Geometric Standard Deviation	95th Percentile	Maximum
Children	1-NAP	0.018 (0.018)	0.452	0.949	0.086	6.61	2.24	5.48
	2-NAP	0.583 (13.2)	22.2	25.4	12.2	3.34	92.1	108
	naphthols	0.527 (15.8)	23.4	22.8	13.8	3.22	78.5	103
	1-FLU	0.015 (0.018)	0.045	0.088	0.028	2.17	0.120	0.689
	2-FLU	0.018 (0.099)	0.130	0.121	0.098	2.17	0.312	0.719
	3-FLU	0.015 (0.018)	0.042	0.089	0.027	2.06	0.106	0.716
	Summed FLU Metabolites	0.053 (0.142)	0.217	0.282	0.160	2.01	0.589	2.124
	1-PHE	0.018 (0.069)	0.104	0.145	0.067	2.43	0.252	0.997
	2-PHE	0.017 (0.037)	0.069	0.119	0.042	2.39	0.164	0.887
	3,4-PHE	0.031 (0.077)	0.124	0.229	0.078	2.25	0.287	1.74
	Summed PHE Metabolites	0.068 (0.189)	0.297	0.487	0.195	2.20	0.709	3.62
	1-PYR	0.018 (0.073)	0.123	0.236	0.076	2.43	0.254	1.90
Adults	1-NAP	0.018 (0.221)	0.718	1.814	0.120	7.324	2.608	12.772
	2-NAP	1.127 (14.464)	29.859	37.539	14.648	3.598	106.250	163.377
	naphthols	0.820 (14.332)	29.472	34.613	14.629	3.650	98.231	143.686
	1-FLU	0.014 (0.019)	0.088	0.206	0.034	2.907	0.421	0.988
	2-FLU	0.018 (0.108)	0.223	0.350	0.121	2.810	0.813	1.707
	3-FLU	0.018 (0.018)	0.082	0.189	0.034	2.837	0.408	1.322
	Summed FLU Metabolites	0.053 (0.170)	0.394	0.723	0.199	2.692	1.516	3.925
	1-PHE	0.018 (0.076)	0.152	0.299	0.081	2.694	0.495	2.220
	2-PHE	0.018 (0.040)	0.079	0.114	0.045	2.643	0.234	0.750
	3,4-PHE	0.033 (0.051)	0.129	0.211	0.073	2.480	0.371	1.274
	Summed PHE Metabolites	0.071 (0.192)	0.360	0.579	0.213	2.428	1.044	3.726
	1-PYR	0.016 (0.067)	0.116	0.129	0.073	2.619	0.383	0.652

The top 50% of children's metabolite concentrations are higher than adults within the same household, shown by the fact that the medians of the child/adult ratios are approximately 1 and the arithmetic means of the child/adult ratios are greater than one **(Table 5).** Participating home 174, 146 and 103 had the highest child/adult ratios for 1-NAP metabolite concentrations **(Table 6).** Five out of the ten participating households with the highest 1-NAP concentrations in the 90th percentile reported the use of pesticides in the home in the last six months. Three of these households had elevated urinary metabolites among adults only, one household had elevated metabolites among both the adult and child, and one in which elevated metabolites were among the child only. All of these homes used pesticides products designed to kill cockroaches, but some also reported using products designed to kill ants, flying insects or spiders as well. Among the 51% of urine samples (61) that were very low, and below the limit of quantification for 1-NAP, there were 10 households in which participants reported using pesticides in the last six months.

Smoking and Vaping

Nicotine metabolites, cotinine (COT) and trans-3'-hydroxycotinine (3HC) are significantly, positively correlated with each other (p-value < 0.001). COT and 3HC are significantly, positively correlated with urinary NAP and FLU metabolites (p-values < 0.05) **(Figure 13).** To determine whether correlations were driven by outliers, we evaluated the log-log relationships of these variables as well **(Figure 12).**

Figure 13. Summed Urinary NAP and FLU and COT Metabolite Concentrations

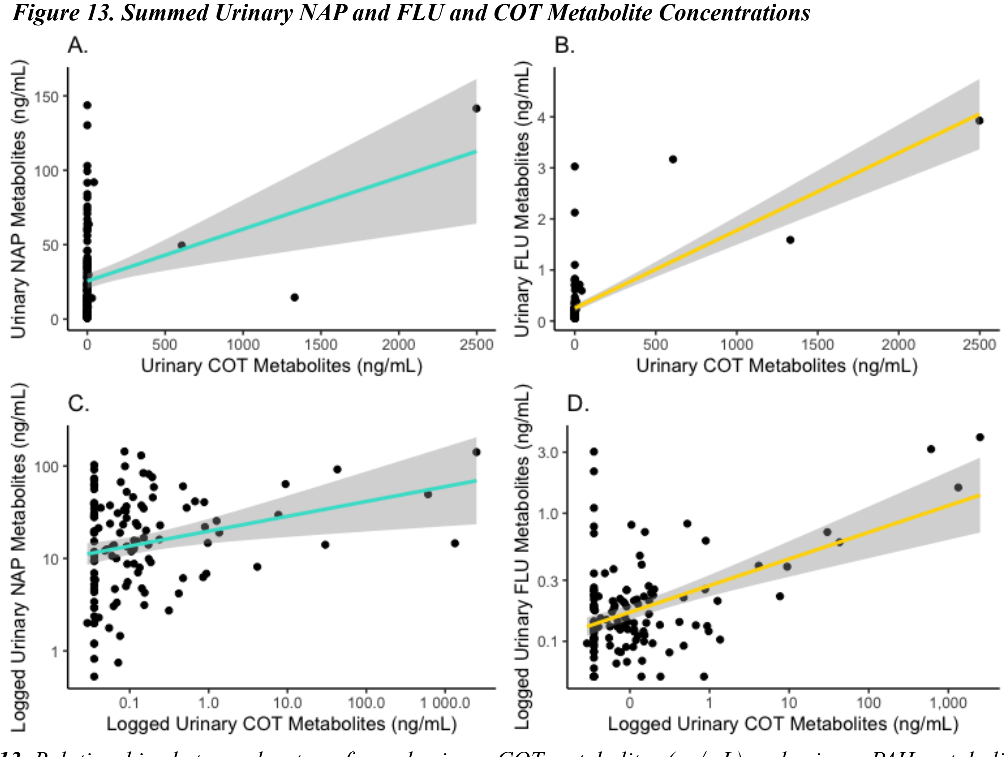

Figure 13. *Relationships between log-transformed urinary COT metabolites (ng/mL) and urinary PAH metabolite concentrations (ng/mL). Values from adults and children are combined (regression line formula: $Y_i = \beta_0 + \beta_1 X_1 + \varepsilon$). For PAH compounds with multiple metabolite compounds measured (NAP, FLU, and PHE), respective metabolite compounds for each PAH were summed to represent values displayed in plots. A. Urinary COT and NAP metabolite concentrations. B. Urinary COT and FLU metabolite concentrations. C. Urinary COT and PHE metabolite concentrations. D. Urinary COT and PYR metabolite concentrations.*

When asked if participants smoked or vaped during the study period, only one participant reported actively smoking cannabis. Other participants reported being exposed to second-hand smoking or vaping. Urinary PAH metabolite concentrations are presented in **Figure 14**. The adult participant that smoked cannabis had the second highest urinary FLU metabolite concentration (a summed FLU concentration of 3.16 ng/mL) in this study population. They also reported that their child was in the home while smoking occurred, and the child had a summed urinary FLU metabolite concentration of 0.25 ng/mL. The child and adult participants from this home had significantly higher urinary FLU metabolites than participants from non-smoking homes (p-value = 0.05)

Two participants reported being inside when someone used electronic cigarettes (vape/e-cig), however it was not reported whether tobacco or cannabis were used. These participants also reported that children were in the home when vaping was occurring. In bivariate linear regression models, adult and child participants in home where smoking and vaping was reported had significantly higher urinary FLU, PHE, and PYR metabolites, as well as COT and 3HC metabolites (p-value = 0.05) compared to other study participants. Participant 146 reported vaping during midday and evening of day 1 and on the morning of day 2 of the study period. Participant 168 reported vaping during midday and evening of day 1.

Participant 155 reported that a visiting family member smoked outside. This participant had the highest FLU metabolite concentrations as well as COT. Another participant (180) reported being indoors when someone else smoked cigarettes in a location other than their home, however there was no evidence of a statistical difference between the urinary metabolites for this participant and others. Their child was not in the same location where the cigarettes were smoked, and these participants did not have elevated COT or 3HC metabolite concentrations.

Figure 14. Urinary PAH Metabolites among Smoking and Vaping Participants

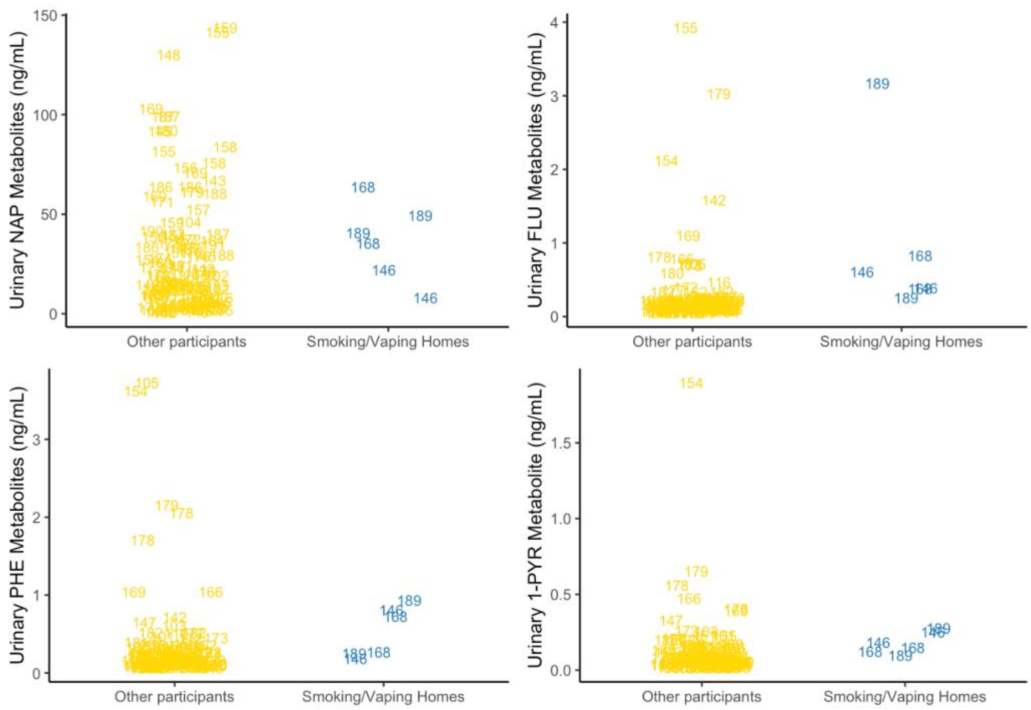

Figure 14. *Urinary NAP, FLU, PHE, and PYR metabolite concentrations (ng/mL) among participants who reported smoking or vaping at home during the study period and those that reported not smoking or vaping.*

Ventilation and Air Filtration

Adults who reported sleeping in a bedroom with an open window the night before providing their urine sample had significantly lower urinary naphthols concentrations than adults that did not sleep with an open window (p-value < 0.05) **(Figure 15).** Sleeping with an open window was also significantly associated with lower 2-NAP metabolite concentrations (p-value > 0.001), which likely drove the association with the summed naphthols. The log difference in 2-naphthol between those who slept with an open window and those who did not was -1.2; this suggests that people who slept with an open window in their room had approximately 70% lower urinary 2-NAP concentrations. There was no evidence of an association between sleeping in a room with an open window and other urinary PAH metabolites. Adults were also asked if children slept in a room with an open window. We did not find an association between the urinary PAH metabolites of children and whether they slept in a room with an open window. Households that opened windows during the study period also showed increased summed urinary naphthols concentrations (p-value = 0.054).

Figure 15. Urinary 2-Naphthol Concentration & Open Windows

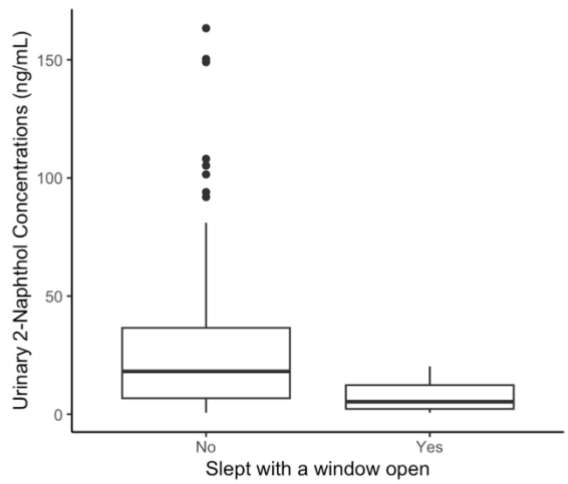

Figure 15. *Urinary 2-naphthol concentrations among participants who reported sleeping with windows open during the study period and those who did not.*

Portable air filter use and exhaust fan use were continuous variables measuring the number of times these devices were turned on by participant. In bivariate log-linear regressions, each additional time they were used on a continuous scale resulted in a slight increase in urinary 2-NAP metabolite concentrations**.** Eight participants reported using portable air filters in their home during the study period. Using portable air filter was significantly associated with a small increase in urinary 2-NAP concentrations (p-value < 0.05) in bivariate models or an 18% increase in 2-NAP each time the portable air filters were used during the study period. Seven of these 8 homes reported having their filter on all or most of the time and they were located in various rooms of the house, from the adult's or child's bedrooms to the kitchen or main living area of the home.

Figure 16. Urinary Concentrations of 2-NAP & Exhaust Fan Use

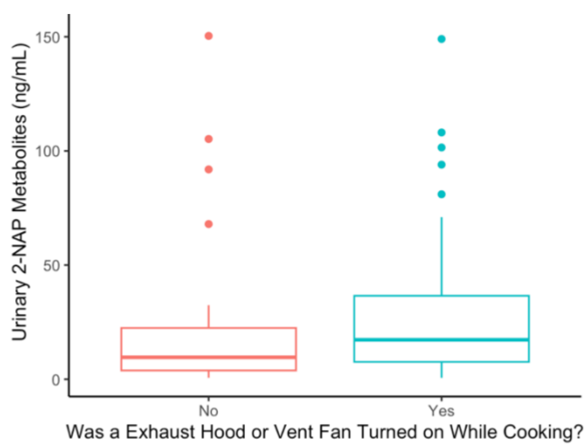

Figure 16. *Urinary 2-naphthol concentrations among participants who reported using a kitchen exhaust fan while cooking during the study period and those who did not.*

Almost all (95%) of participants reported having an exhaust hood or vent fan in their kitchen, and among them, almost all (90%) reported using it either "sometimes" or "every time" during cooking. There were no significant differences among the urinary metabolites of adults and children based on reported exhaust hood use. Seventy-three percent of participants used an exhaust hood or vent fan while cooking and reported turning the fan on between 1-7 times during the study period. Twenty-six percent of participants did not use an exhaust hood or vent fan while cooking. Each time an exhaust hood or vent fan was turned on while cooking was associated a significant increase in logtransformed urinary 2-NAP of 0.15, indicating a 16% increase in urinary 2-NAP concentrations (p-value > 0.05) **(Figure 16).** These findings for increased 2-NAP concentrations with exhaust fan or air filter use were still significant after excluding homes where smoking and vaping occurred.

Dietary Exposure

Adult participants were also asked about how many times they themselves or their participating child ate food that was fried, grilled, barbequed, smoked, or roasted on the day prior to the collection of their urine sample. We did not detect an association between dietary consumption of these foods and urinary PAH metabolites.

Cooking

There are similar numbers of study participants who use gas stoves compared to electric stoves, however people with gas stoves have lower urinary metabolites than electric stove users. Homes that reported using the gas stove today and yesterday had significantly higher FLU and PHE urinary metabolites among children, but not among adults. There were no significant differences between children and adults in homes using electric stoves during the sampling period.

Participants reported the number of times the stove was used for frying food during the study period. When all participants (adults and children) were grouped together, there was a 0.19 increase in the log transformed naphthols concentrations (driven by 2-NAP) for each additional instance of frying performed on the stove. This indicated there was a 21% increase in urinary naphthols associated with using the stove for frying. This association was significant among adults only, but not among children only.

While use of a gas stove during the study period was associated with significantly increased summed PHE, FLU, naphthols metabolite concentrations (p-value < 0.05), and increased urinary 1-PYR metabolites (p-value = 0.056), there was also increased summed urinary PHE metabolite concentrations associated with use of an electric stove (p-value < 0.05). Increased urinary PHE metabolite concentrations were also associated with using a grill, barbeque or smoker outside of the home during the study period (p-value < 0.05). We did not identify differences between adults' and children's urinary metabolites in regard to these associations.

Eight participants reported using a barbeque or smoker at their home during the study period; six people used it once and two people used it twice. Participants who used a barbeque or smoker had a significant increase in log summed PHE urinary metabolites compared to participants in homes where no barbeque or smoker was used (p-value < 0.05) representing an 85% increase in urinary PHE metabolite concentrations. Other urinary PAH metabolites were not associated with barbeque or smoker use.

Air Fresheners, Candles and Incense

Thirty-eight (59%) participant homes reported regularly using air fresheners or diffusers in their home (almost every day or 3-5 days per week). It was reported by participants that during the study period 32 people (50%) used air freshener spray in their home, 29 (45%) used plug-in air fresheners, and 1 (2%) used solid air fresheners like potpourri. In log linear regressions using log-transformed metabolite data, living in a home where air freshener spray or plug-in air fresheners were used during the study period was significantly associated with increased summed NAP metabolite concentrations among adults and children (p-value > 0.05) **(Figure 17).** This finding was consistent when analyzing adults and children in separate groups as well as analyzing the data all together. After accounting for season, the model results were still significant, with season adding an additional 8-9% of explanatory power to the model. Living in a home where air freshener spray or plug-in air fresheners were used during the study period was also significantly associated with increased summed FLU metabolite concentrations when looking at adult and child data together (p-value > 0.05), but was not significant when adult and child metabolite data were separated. Use of air freshener spray in the home was significantly associated with increased summed PHE metabolite concentrations among adults and among all participants pooled together (p-value < 0.05). This association was not observed for PYR metabolite concentrations. There was also no difference between metabolite concentrations among people that used solid air fresheners and those who did not. We did not find evidence of an association between candle or incense burning and urinary PAH metabolites.

Figure 17. Summed Urinary NAP Concentrations and Air Freshener Use

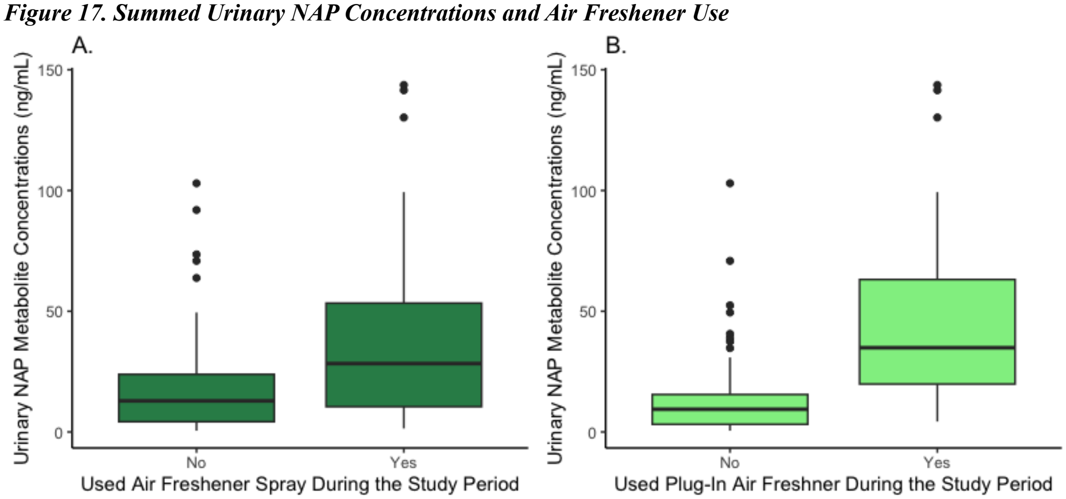

Figure 17. A. Summed urinary NAP metabolite concentrations (ng/mL) among adults and children of participating homes where air freshener spray was used during the study period and those where it was not. B. Summed urinary NAP metabolite concentrations (ng/mL) among adults and children of participating homes where plug-in air freshener was used during the study period and those where it was not.

Personal Care Products and Cleaning Products

Adult participants that reported using deodorant spray both days during the study period had significantly higher summed urinary NAP metabolite concentrations (p-value < 0.05). The same finding was observed among pooled adult and child data, but not among children separately.

Participants that reported using perfume during the study period also had significantly higher summed urinary NAP metabolite concentrations (p-value < 0.05), and the same finding was observed among pooled data as well as adults and children separately. We also investigated self-reported data from questionnaires for use of shampoo, solid deodorant, scented lotion, scented body wash, nail polish, and nail polish remover during the study period and found no associations between these and urinary PAH metabolite concentrations.

Use of either floor cleaner, all-purpose cleaner, restroom cleaner, or bleach individually in the home during the study period was associated with significantly increased summed urinary NAP metabolite concentrations among adults and children separately pooled (p-value < 0.05) **(Figure 18).** Individual use of carpet cleaner or furniture polish in the home was associated with significantly higher urinary NAP metabolite concentrations among adults and children pooled together, but this difference was not significant among adults and children separately. We also investigated use of glass cleaner and disinfectant wipes and found no association with urinary PAH metabolite concentrations. After accounting for season, all of these associations were still significant with the exception of floor cleaner use.

Figure 18. Urinary NAP Metabolite Concentrations and Cleaning Product Use

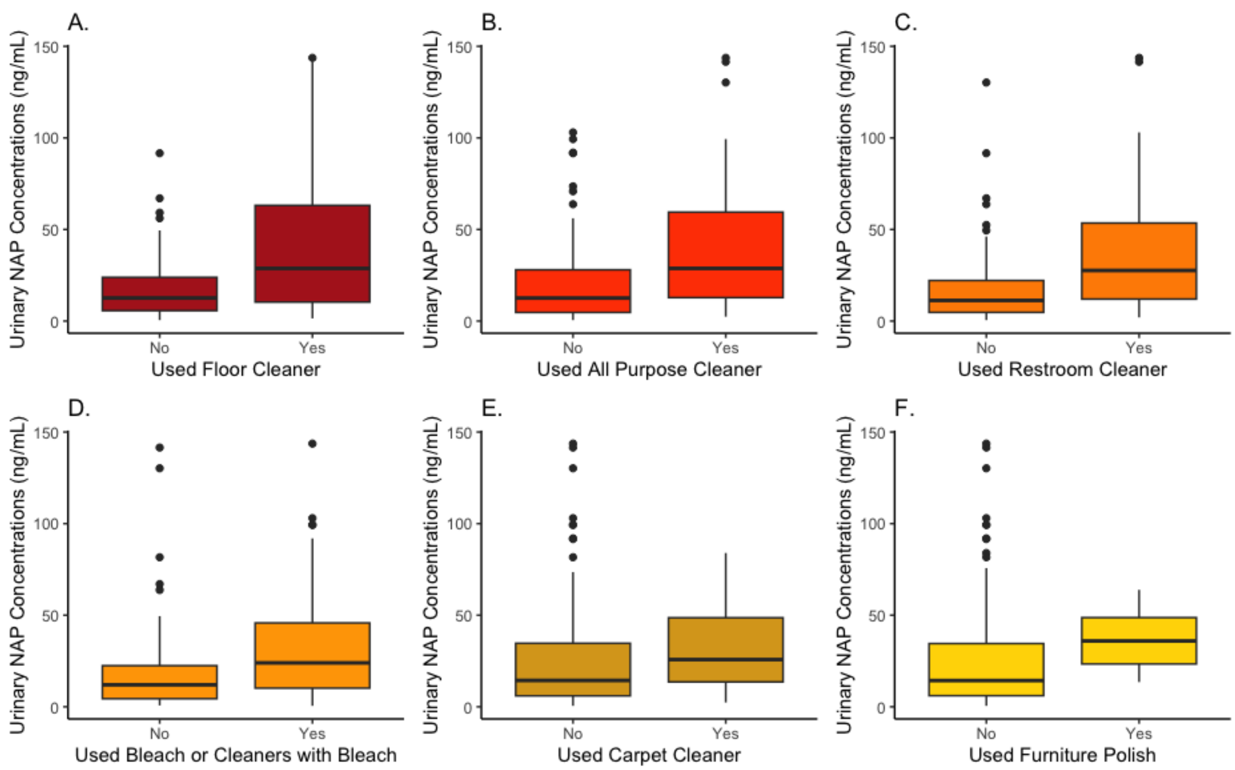

Figure 18. Summed urinary NAP metabolite concentrations (ng/mL) among adults and children and use of cleaning products in the home during the study period. A. Floor cleaner. B. All-purpose cleaner. C. Restroom cleaner. D. Bleach or cleaners with bleach. E. Carpet cleaner. F. Furniture polish. Colors are used to distinguish between cleaning products.

Heating

In a bivariate regression model, using a gas-powered wall-heater or furnace during the study period was associated with significantly lower logtransformed naphthol concentrations (p-value < 0.05), representing a 66% decrease in naphthols compared to those that did not use gas-powered heat. However, when accounting for season it was no longer a significant relationship. When assessed for collinearity, use of gas heat and season both had Variance Inflation Factors of 1, indicating no multicollinearity.

Other Home Characteristics

People that own their home had significantly lower 2-NAP and naphthols, significantly higher 1-NAP, higher 1-FLU (not significant), lower 2-FLU (not significant), higher 3-FLU (not significant), and higher summed FLU (not significant). Regularly parking a vehicle in an attached garage resulted in significantly lower urinary 2-NAP concentrations (p-value < 0.05) and lower FLU metabolites (not significant), which may be confounding the relationship between urinary metabolites and home owners vs. renters because home owners are more likely to have and regularly park in attached garages.

Home proximity to highway 99 was significantly associated with urinary PHE and FLU metabolites (summed and individual metabolites) (p-value < 0.05); however, urinary metabolites were not associated with traffic volume as annual vehicle miles traveled. After separating adults and children, children's urinary FLU metabolites (all three FLU metabolites and sum) were significantly associated with proximity to highway 99, but adults were not. There were no differences between adults and children related to other PAHs and proximity to Highway 99.

Urinary Results Overview

We combined the variables that were significantly associated with urinary PAH metabolites into log-linear multivariate models to evaluate the multiple R squared value, which showed that: Smoking or vaping in the home, frequently opening windows (3 times of more during the study period), sleeping with an open window, using gas-powered heat, frying food, home proximity to Highway 99, regularly parking in an attached garage, and using a portable air filter contributed to 28% of the variability in the summed NAP urinary metabolites. The greatest contributor to this variability was regularly using an attached garage (14%). Diet did not contribute to explaining the variability in urinary NAP metabolites. Use of a gas stove, frying, smoking and vaping in the home contributed to 5% of the variability within the summed PHE urinary metabolites, 3% of which was explained by smoking and vaping. Smoking and vaping in the home contributed the greatest amount of variability (14%) in summed FLU urinary metabolites (13.9%) and 1-PYR urinary metabolites (5%).

2.4 Discussion

Airborne PAH concentrations that we measured in this study are lower than the measurements from many other investigations discussed below. Nevertheless, we identified sources of preventable exposure to PAHs, including smoking, heating, cooking, and traffic-related exposures. Historic air quality challenges lead to decades of PAH monitoring in the city of Fresno; however, PAH monitoring has remained very limited throughout the remainder of the San Joaquin Valley. This study is the second to assess residential exposure to PAHs via integrated sampling in the AB 617 communities of Fresno and the first in Stockton. Our measurements of outdoor NAP at Fresno homes were significantly lower than concentrations measured at a central sampling site in Fresno in 2021 and 2022; however, FLU, PHE, and PYR concentrations we measured were higher.[71] These previously measured concentrations are comparable to our measurements as the same field collection and analytical methods were utilized. Our methods to quantify both vapor and particle phase PAHs were developed to increase sensitivity and precision; however, instrument errors resulted in higher limits of detection than achieved in past analyses.[39] PAHs are time consuming to collect and expensive to analyze, which is why these compounds are not routinely monitored along with other air pollutants at the local air district level.[47] This paper is one of few investigations characterizing both indoor and outdoor residential concentrations.

2.4.1 Putting Airborne PAH Concentrations into Context

Ambient average NAP concentrations collected by the US EPA from 2018 to 2022 ranged from 20 – 60 ng/m^3 and maximum concentrations ranged from 660 – 2,660 ng/m^3 at monitoring locations across the United States. Outdoor concentrations measured in this investigation were lower than these values, with a mean of 40 ng/m^3 and a maximum of 200 ng/m^3. Outdoor ambient NAP concentrations measured in urban Southern California communities in 2001-2002 that were also in or adjacent to AB 617 communities were also higher than the levels we measured in this study: 92-513 ng/m^3 in Riverside and 46-178 ng/m^3 in Long Beach.[72] Regulations in California governing traffic emissions, residential wood burning, and agricultural burning as well as advancements in engine technology have resulted in lower ambient PAH concentrations measured in Fresno over the last twenty years. As a result, particle-bound PAH concentrations in Fresno decreased from 10.9 ng/m^3 in 2001 to 4.1 ng/m^3 in 2018, representing a 62% decline. Our detection frequencies of airborne PAHs are much lower than we expected, possibly due to the recent reductions in PAH air pollution in this region and throughout the state.

In a recent review of the NAP literature, ATSDR reported indoor concentrations ranging from 178 – 996 ng/m^3.[9] Average indoor NAP concentrations ranged from 180 to 284 ng/m^3 in a study of 288 urban and suburban homes in southeast Michigan, published in 2011.[73] In another study of ten urban, non-smoking homes in Chicago in 1994-1995, the average NAP concentration was 851 ng/m^3.[74] The indoor concentrations measured in this investigation are also substantially lower than these reported values, with a mean of 45 ng/m^3, 75th percentile of 58 ng/m^3, and the maximum of 261 ng/m^3. Indoor samples collected from 55 non-smoking residences in Los Angeles in 1999-2000 were similar to the levels we measured (16-220 ng/m^3).

Although PAH concentrations collected in this investigation in Stockton were higher than in Fresno, average indoor and outdoor concentrations we measured of FLU (2.0-4.0 ng/m^3), PHE (3.5-10.1 ng/m^3) and PYR (3.1-3.6 ng/m^3) in Stockton homes in 2024 were higher than those collected at Stockton schools in 2023 via identical sampling methods (1.1-1.5 ng/m^3 of FLU; 2.7-3.3 ng/m^3 of PHE; and 0.3-0.4 ng/m^3 of PYR). In contrast, NAP concentrations we measured were on average an order of magnitude lower than those measured in Stockton schools.[75] Overall, city did not play a meaningful role in explaining the variation in airborne PAH concentrations in our study, and may have been confounded by seasonal differences. Fifty percent of Stockton (n=9) samples were collected in the spring and 50% were collected in the summer, whereas Fresno samples were collected across spring, summer and fall seasons.

2.4.2 Indoor Infiltration of Outdoor PAHs in Air

Seasonal variation in PAH levels has been well-documented, with higher winter concentrations due to temperature inversions and lower mixing heights.[47,72] A disadvantage of this study is the lack of monitoring during the winter months because of an administrative delay in the project start date, which prevented participant recruitment prior to the spring of 2023. Nevertheless, our findings are consistent with other literature showing a seasonal effect. In our analysis, we observed higher outdoor concentrations and higher indoor concentrations in the spring season. The correlation between outdoor and indoor concentrations by season suggests infiltration of outdoor concentrations into residences. Temperature and wind speed were significant variables that added explanatory power in our models, illustrating that season alone was not sufficient in characterizing the variability in PAH concentrations. Correlation of outdoor and indoor PAH concentrations indicates that they are originating from the same sources. Migration and infiltration of outdoor concentrations into the indoor environment has been well-documented, particularly among PAHs that readily partition into the gas phase.[76,77] Frequently opening windows in the home (3 times or more over the 24-hour sampling period) was significantly associated with higher indoor NAP concentrations in our investigation, indicating an infiltration effect of outdoor NAP into homes. Additionally, traffic volume and proximity was associated with significantly increased FLU concentrations in outdoor air and indoor air, suggesting outdoor infiltration.

2.4.3 Urinary PAH Metabolites and Health Relevance of Exposure

The Agency for Toxic Substances and Disease Registry established a Minimum Risk Level (MRL) for chronic inhalation exposure to NAP of 4000 ng/m^3. An MRL is an exposure level at which it is anticipated that chronic, non-occupational exposure will cause adverse health outcomes. The respiratory tract and immune system are the most sensitive target organ systems affected by inhalation of NAP ("endpoints"), and were therefore used to derive this MRL.[78] MRLs have not been established for inhalation exposure to FLU, PHE or PYR. Although NAP concentrations measured in this investigation are below the MRL, as well as below occupational exposure limits, there may be risks of cellular level toxicity and oxidative stress at chronic exposures below these levels. These exposure guidelines did not evaluate cellular toxicity and oxidative stress effects, and adverse effects may occur below these recommended levels. There is evidence that PAHs induce oxidative stress, damage DNA, and contribute to a reduced capacity for DNA repair.[55] PAH exposures often occur in mixtures because of the nature of their production and because they exist in complex combinations with other air pollutants. Adverse health effects of PAHs in human populations are difficult to disentangle given the other air pollutants they are often in combination with; however, the myriad evidence of cellular cytotoxicity, genotoxicity, and oxidative stress provides compelling evidence for the toxicity and carcinogenicity potential of PAHs. In a study of temple workers exposed to incense, where urinary 1-PYR was significantly elevated compared to unexposed controls, exposed workers also had significantly increased DNA damage, measured as biomarkers of 8-hydroxy-2'deoxyguanosine (8-OHdG) and DNA strand breaks, and decreased DNA repair capacity, measured with the cytogenetic challenge assay, compared to controls.[55]

Urinary metabolite data contributes to the body of knowledge on exposure and metabolism of PAHs, which is not well understood. PAHs are thought to become carcinogenic after they become hydroxylated via metabolic activation in the body.[79] Urinary PAH metabolites generally increase in the hours after exposure and return to background concentrations within 24-48 hours.[80] Inhalation and ingestion of PAHs are the primary contributors of urinary PAH metabolites reported in the literature. PAHs had been found in foods that have been baked, roasted, toasted, grilled, fried, or smoked, as well as vegetables and fruits that are exposed to PAHs in the environment during production.[54] Median half-lives after dietary exposure range from 2.9 – 6.1 hours.[80] Elimination kinetics of PAHs were investigated in a study of 8 smokers in the U.S.; after active tobacco smoking, half-lives ranged between: 4.9-12.2 hours for 2-NAP, (mean = 9.4 hours); 2.8-7.7 hours for 1-FLU (mean = 5.5 hours); 2.5-5.0 hours for 2-FLU (mean = 4.1 hours); 1.4-11.9 hours for 3-FLU (mean = 8.2 hours); 3.7-9.9 hours for 1-PYR (mean = 6.0 hours). PHE half-lives were not detectable due to very low concentrations. Half-lives of 1-PYR after inhalation to PAHs among occupationally exposed workers have been reported to be higher than these, in the range of 13-18 hours, possibly due to continuous exposure at higher concentrations.[81,82] Individual differences in metabolism and excretion rates related to age, genetic factors, and health and hydration status, result in variability in metabolite concentrations. A portion of parent PAH compounds are excreted in urine, and are thought to be primarily excreted in feces, especially for higher molecular weight compounds. There have also been documented differences in metabolite concentrations across different studied populations.[83]

2.4.4 Relationship Between Airborne PAHs and Urinary PAH Metabolites

Overall, literature on the relationship between airborne PAHs and urinary PAH metabolites is inconsistent. In an analysis of PAH urinary metabolite data from the National Health and Nutrition Examination Survey (NHANES) from 2001-2006, annual outdoor $PM_{2.5}$ average concentrations were not associated with levels of urinary NAP, PHE, FLU, or PYR metabolites.[54] This is possibly due to the low variability in the modeled annual PM2.5 concentrations. The variability in airborne FLU, PHE and PYR data from our study is also relatively low due to instrument error resulting in a larger limit of detection than in previous analyses, and we were not able to detect associations between airborne PAH concentrations and urinary PAH metabolite concentrations.

Airborne concentrations and urinary metabolites of PHE and PYR were significantly associated in a study of 204 male school children in 2013 in Saudi Arabia. PHE was the most abundant compound measured among the 14 PAHs, with mean concentrations of total (vapor- and particle-phase) 21.15, 16.83, and 8.65 ng/m^3 across the three sampling sites.[84] These sampling sites were in areas heavily trafficked by vehicles, and measured values are higher than the median PHE concentration of 4 ng/m^3 and maximum PHE concentration of 9 ng/m^3 that we measured in outdoor air. Measured vapor-phase and particle-bound PYR (6.23, 4.15, and 0.82 ng/m^3) were predominantly in the vapor-phase in these measurements, and were in the range of PYR air concentrations measured in this study (2-9 ng/m^3), with a median of 3 ng/m^3.[84] 1-PYR metabolite results from this study population were higher than other study populations where 1-PYR has been measured. After controlling for consumption of charbroiled foods, airborne PYR and PHE were associated with increased unadjusted urinary 1-PYR and PHE metabolite concentrations. This was not statistically significant among the creatine-adjusted urinary metabolites, but still showed an association. Airborne PAH concentrations are also higher compared to studies measuring PHE and PYR, indicating that airborne environmental exposure may be correlated with urinary metabolites, however a stronger link can be drawn when airborne PAHs concentrations are relatively high.

In a study of occupational exposure to airborne PAH pollution and unmetabolized urinary PAH concentrations to NAP and PHE, air concentrations and urinary metabolite levels were correlated, which may be due to the fact that occupational exposure levels are often much higher than those experienced by the general public.[85] Authors compared the unmetabolized urinary NAP and PHE they measured with previously published NAP and PHE air concentrations measured among the same occupational groups (diesel-exposed workers, asphalt workers, coke-producing and aluminum workers), finding elevated post-shift urinary parent compound concentrations of 17,100 - 3,450,000 ng/m^3 and 2,670 – 1,250,000 ng/m^3 for NAP and PHE, respectively. In a study of urinary PAH biomarkers after ingestion of smoked salmon, however, parent PAHs made up 0%, 14%, 42% and 56% for NAP, FLU, PHE, and PYR, respectively.[86] This reflects the variability of unmetabolized parent PAHs in urine; it is not possible to directly compare these concentrations to other studies of PAH metabolites.

We found higher PAH air concentrations among homes that were owned as compared to homes that were rented, which may be driven by the increased presence and use of attached garages among owners. Among the owners, 69% of them (20) also regularly parked in an attached garage, however only 4 renters regularly parked in attached garages. Indoor FLU concentrations were significantly higher in homes where residents regularly parked their vehicle in an attached garage (n=24). People that own their home had significantly lower 2-NAP and naphthols, significantly higher 1-NAP, higher 1-FLU (not significant), lower 2-FLU (not significant), higher 3-FLU (not significant), and higher summed FLU (not significant). Regularly parking a vehicle in an attached garage resulted in significantly lower urinary 2-NAP concentrations (p-value < 0.05) and lower FLU metabolites (not significant), which may be confounding the relationship between urinary metabolites and home owners vs. renters because home owners are more likely to have and regularly park in attached garages.

A similar number of renters versus owners lived within 5 km of Highway 99. Highway proximity does not appear to be driving the PAH concentration differences between home type, however other ambient local air pollution sources by neighborhood may play a role. Mobile homes may generally have higher infiltration rates than other home types due to less well-sealed windows and doors, and older homes are particularly indicative of higher infiltration rates. Mobile homes in this study were all built before 1973, indicating a higher likelihood of infiltration of outdoor air.

Home proximity to highway 99 was significantly associated with urinary PHE and FLU metabolites (summed and individual metabolites) (p-value < 0.05), however urinary metabolites were not associated with traffic volume as annual vehicle miles traveled within a 250-meter buffer. After separating adults and children, children's urinary FLU metabolites (all three FLU metabolites and sum) were significantly associated with proximity to highway 99, but adults were not. There were no differences between adults and children related to other PAHs and proximity to Highway 99. Children are more likely to go to school near the home and their school air concentrations may more closely reflect their home's concentrations versus adults who are more likely to travel farther from home for work.

2.4.5 Sources of Indoor PAH Exposure

Indoor NAP concentrations we measured were on average double NAP outdoor concentrations, which is consistent with findings in the literature of higher indoor levels than outdoors levels due to myriad indoor sources, including cooking, smoking, heating, burning wood, candles, or incense, as well as the use of some household products, such as mothballs, deodorizers, air fresheners, sealants, and adhesives.[73] A large amount of variation has been reported in indoor NAP concentrations within and between studies due to the many different indoor sources as well as variability of outdoor air infiltration among homes.[73] The low concentrations measured and detection frequency of 58% of indoor NAP may contribute to our inability to detect associations between airborne NAP and the self-reported use of indoor products. However, we detected associations between significantly increased urinary NAP metabolite concentrations and the use of air fresheners, cleaning products, deodorant spray and perfume, independent of season, indicating that NAP exposure may be related to the use of these products. Cleaning products are known to be sources of volatile organic compounds but have not been reported to contain NAP specifically. The lack of transparency in ingredient disclosure obfuscates our understanding of exposure from these products.[87] It's possible that NAP is an intentional ingredient, an unintentional contaminant, or simply a generated biproduct of normal use.

Residential wood burning and use of gas-powered heating are also known sources of indoor PAH pollution.[88] Due to the timing of this investigation between late February and September of 2023, there were few participants who heated their home on air sample collection days. Our analysis illustrated that heating the home with a gas-powered furnace (n=6) was significantly associated with increased indoor concentrations of all four PAHs. Burning candles was significantly associated with increased PYR concentrations (n=8). It is consistently reported in literature that burning candles and incense are sources of PAHs; however, we did not detect an effect of burning incense on indoor PAH concentrations, possibly because few participants burned incense (n=3). In a study of incense exposure in Thailand temples, FLU was the third most abundant airborne PAH out of ten compounds measured and urinary 1-PYR was significantly elevated among the 40 temple workers as compared to unexposed controls. Although burning candles and home heating were significantly associated with indoor PAH concentrations, we did not find evidence of an association between these sources and urinary PAH metabolite concentrations. Residential smoking has been identified as a substantial source of indoor PAHs, estimated to contribute to 87% of the total PAHs in the home.[89] We did not see evidence of significant differences between homes where smoking and vaping occurred and homes with no smoking or vaping due the very small number of participants that reported smoking and vaping during the study period (n=4); however, two of these homes (144 and 175) were in the 90^{th} percentile of indoor PYR concentrations, indicating that smoking or vaping in the home may contribute to elevated PYR. Participants in these homes did not report burning candles or incense.

Urinary PAH metabolite levels have been found in the literature to be higher in homes with smokers.[79] Current smoking status was reported to account for 10-47% of the variability of urinary PAH metabolites, and the single largest explanatory variable, in an analysis of NHANES data.[54] In a separate analysis of NHANES data from 2003-2008, smoking and second-hand smoke exposure were both significantly associated with NAP, PHE, FLU, and PYR urinary metabolites.[90] We found evidence that smoking and vaping emissions is associated with elevated urinary FLU metabolites. Particularly, the active smoking of cannabis resulted in the highest observed FLU metabolite concentration among this study population. Additionally, we found the urinary FLU and nicotine metabolites (COT and 3HC) were highly correlated, indicating that tobacco-related exposure contributes to urinary FLU metabolite levels. 1-FLU has been found to be significantly associated with smoking elsewhere, with 5-fold higher concentrations in smokers compared to non-smokers in Poland, and 25-fold higher concentrations in smokers versus non-smokers in the United States.[83] 1-FLU followed by 2-NAP were much more selective of tobacco smoke exposure than PHE metabolites and 1-PYR.

Participant 189 actively smoked cannabis and reported that their child was in the home while smoking occurred. The adult participant had the second highest urinary summed FLU metabolite concentration, and the child had a summed urinary FLU metabolite concentration of 0.25 ng/mL, which is between the 75^{th} and 95^{th} percentile of children's urinary metabolite concentrations. The child and adult participants from this home had significantly higher urinary FLU metabolites than participants from non-smoking homes (p-value = 0.05).

Two participants reported vaping in their home midday and in the evening on day 1 of the study period, and one of them additionally reported vaping in their home the morning of day 2 of the study period. The timing of these exposures to second-hand vape emissions is likely to fall within the half-life window of urinary PAH metabolites. The timing of smoking cannabis in one participant's home was not reported. Although it was not reported whether the two participants who vaped were exposed to tobacco or cannabis e-cig/vape emissions, it's possible that it was tobacco given that these participants had significantly higher urinary nicotine metabolites in addition to urinary FLU, PHE, and PYR metabolites (p-value = 0.05).

Active smoking resulted in higher urinary PAH metabolites than second-hand smoking or vaping exposure. One participant reported exposure to tobacco cigarettes, however it was not inside their home, and it may have been a small enough exposure to not be detected in urinary metabolites. Another participant reported that a visiting family member smoked outside of the home, and his participant had the highest observed urinary FLU metabolite concentration and the highest nicotine metabolite concentrations in the study population, suggesting that second-hand and possibly third-hand smoke contributed to these exposures. The participant that smoked cannabis in the home also reported burning incense two times during the study period, which may have contributed to their urinary metabolite concentrations.

Adult and child participants in homes where smoking and vaping was reported (146, 168, and 189) had significantly higher urinary FLU, PHE, and PYR metabolites, as well as COT and 3HC metabolites (p-value = 0.05) compared to other study participants, indicating that tobacco-related exposure was a major source of PAH exposure in this study population and that there are other dominant sources of NAP exposure beyond smoking and vaping.

Although elevated concentrations PAHs are generated from cooking with solid fuels like charcoal or wood, cooking with natural gas is nevertheless documented as a significant source of PAHs in residential environments.[89] Consistent with this literature, we found evidence that use of a gas stove or gas oven during the 24-hour sampling period was associated with higher airborne PAH concentrations in homes, particularly NAP.

A substantial source of PAHs in food originates from high-temperature cooking including grilling, smoking, barbequing, and frying.[91] These types of cooking have been shown to emit high concentrations of PAHs.[92] For each additional time participant's reported frying food during the sample collection period, there was a 0.19 increase in the log transformed naphthols concentrations (driven by 2-NAP). This indicated there was a 21% increase in urinary naphthols concentrations associated with using the stove for frying. Approximately a third of participants reported having an electric stove, therefore this finding indicates the act of frying itself may generate NAP, which is consistent with the literature. When we investigated adult's and children's urinary metabolites separately, we found that adult's urinary metabolite concentrations were significantly associated with increased frequency of frying, however children's were not. Since children were not performing the frying, this indicates cooking-related NAP exposure for adults.

We did not detect an association between indoor or outdoor PAH concentrations and the use of a barbeque among study participants, likely because there were only 8 participants who used a barbeque on the sampling day, and it is not known where they used the barbeque outside in relation to where the outdoor air monitor was. Personal air monitoring (air monitors worn by participants) would have been better able to characterize personal cooking-related exposures to airborne PAHs than the stationary (area sample) monitors which were placed in living rooms versus kitchens, and not necessarily near outdoor barbeques. Nevertheless, we found evidence of barbeque-related exposure to PAHs via urinary metabolite data. Participants who used a barbeque or smoker had a significant increase in PHE urinary metabolites compared to participants in homes where no barbeque or smoker was used, representing an 85% increase in urinary PHE metabolite concentrations. In this way, urinary biomarkers or exposure can fill a gap in airborne exposure assessment that may miss other routes of exposure, like ingestion.

While use of a gas stove during the 24-hour sampling period was associated with significantly increased summed PHE, FLU, naphthols metabolite concentrations (p-value < 0.05), and increased urinary 1-PYR metabolites (p-value = 0.056), there was also increased summed urinary PHE metabolite concentrations associated with use of an electric stove (p-value < 0.05). Increased urinary PHE metabolite concentrations were also associated with using a grill, barbeque or smoker outside of the home during the study period (p-value < 0.05). We did not identify differences between adults' and children's urinary metabolites in regard to these associations, however this finding points to additional evidence that that act of cooking, regardless of stove-type, contributes to exposure. Cooking-related exposure may confound the documented relationships between dietary exposures and urinary PAH metabolite concentrations.

We did not find evidence of an association between PAH air concentrations and the use of portable air filters in the home, or exhaust hoods or vent fans used while cooking. However, as mentioned previously, the study was not designed to evaluate the direct effect of cooking-related PAH exposures nor to evaluate the effectiveness of ventilation and air filtration. Without personal monitoring data, we cannot infer the impact of ventilation and air filtration because we don't know where participants spent time in the home. Using a portable air filter in the home during the 24-hour sampling period (n=8) was associated with a significant but small increase in urinary 2-NAP concentrations. Similarly, using an exhaust hood or vent fan while cooking was associated with a significant but small increase in urinary 2-NAP. Explanations for these findings include that people tend to close windows and doors while air filters are in use and that cooking-related PAH air pollution may have been generated and inhaled prior to the vent fan being turned on. Additionally, it is possible that people experiencing more air pollution are more likely to use portable air filters. Because air monitors were not placed in kitchens or worn by participants, we were not able to identify cooking-related peaks in exposure.

Air filters have been widely documented to effectively remove particulate matter from indoor air; however, NAP and other gases are not effectively removed using most household air filters. NAP, PHE, and FLU predominantly exist in the vapor-phase, whereas PYR predominately exists in the particle-phase.[84] Volatile gases are unlikely to be captured or attenuated by most portable air filters, therefore the only PAH that might be reduced may be PYR, which would be removed via particle filtration. There is also extensive literature showing that exhaust hoods and vent fans used while cooking are beneficial in reducing exposure by pulling the cooking-related air pollutants away from the cook's breathing zone.[93]

Frequently opening windows (3 or more times) during the 24-hour sample collection period was associated with increased indoor NAP concentrations. Households that opened windows during the study period also showed increased summed urinary naphthols concentrations (p-value = 0.054). Some studies have shown higher daytime airborne PAHs concentrations, predominantly due to traffic emissions than nighttime concentrations.[94] Adults who reported sleeping in a bedroom with an open window the night before providing their urine sample had significantly lower urinary naphthols concentrations than adults that did not sleep with an open window.

2.4.6 Relationship Between Diet, Pesticides and Urinary Metabolites

Diet has been reported as a significant predictor of PAH urinary metabolites, with two studies showing the dietary sources represented 90% of the contribution of urinary PAH metabolites among non-smoking college students and pregnant women.[95,96] Urinary PAH exposures among school children in Saudi Arabia (median age 11) who consumed charbroiled foods had a statistically significant 19% increase in urinary creatinine-adjusted PHE metabolites and a 17% increase in urinary creatinine-adjusted 1-PYR metabolites.

Other studies have reported no associations between dietary exposure and urinary PAH metabolites. Although diet was not associated with urinary PAH metabolites in the analysis of NHANES data by Navarro et al., recall bias among participants and high variability in PAH concentrations in food may have contributed to a lack of precision in the exposure measure. Similarly, we did not find associations between diet and urinary PAH metabolite concentrations. Contributing reasons for this finding may be recall bias among participants, high variability in PAH concentrations within various foods, high variability in the PAH metabolism and excretion of metabolites, and lastly, a lack of precision in the exposure measure. Adult participants were asked if they or their children had eaten food that was fried, roasted, grilled, smoked, or barbequed yesterday. If these foods were eaten in the middle of the day or even for an early dinner, any resulting PAH metabolites may have been excreted prior to the collection of the "first morning void" urine sample collection the next day due to the short half-life of these compounds in the body. A dinner time exposure to these foods may have resulted in metabolites in the urine, however we did not collect information about the timing of their consumption of these foods. These sources of variability resulted in us not seeing any effect of dietary exposure on urinary metabolites, which has similarly been found in other studies.

Both NAP and the pesticide, carbaryl, can be metabolized and excreted as urinary 1-NAP, but not 2-NAP. We evaluated the relationship between 1-NAP and 2-NAP to investigate the possibility of carbaryl as a source of exposure. Urinary 1-NAP concentrations were significantly lower than 2-NAP, with an average ratio of 1-NAP to 2-NAP of 0.05, indicating that carbaryl is not likely a source of exposure.[97] However, when specifically investigating the households with the highest 1-NAP metabolite concentrations, five out of the ten homes reported using pesticides in the home in the last six months. All of these homes used pesticides products designed to kill cockroaches, but some also reported using products designed to kill ants, flying insects or spiders as well. Among the 90th percentile of 1-NAP concentrations in urine, 50% were from homes reporting use of pesticides in the last six months. There were fewer households (only 16%) reporting use of pesticides in the last six months among the lowest, non-detectable concentrations of 1-NAP. All of these participants reported using pesticides to treat cockroaches, and a few reported the use of pesticides to treat other pests as well, including ants, fleas, and flying insects. Therefore, carbaryl-containing pesticide products may be the source of elevated 1-NAP urinary metabolites in this population.

2.4.7 Urinary Analysis Conclusions

The quantitative PAH air concentrations we collected were not associated with the urinary PAH metabolites, suggesting that personal exposures to airborne PAHs may have been different from the area samples we collected in the home and that other sources of PAHs explain the urinary PAH metabolite concentrations. The qualitative data we collected in our questionnaire was able to explain a small to moderate portion of the variability in urinary PAH metabolite concentrations. Smoking or vaping in the home, frequently opening windows, sleeping with an open window, using gas-powered heat, frying food, home proximity to Highway 99, regularly parking in an attached garage, and using a portable air filter contributed to 28% of the variability in the naphthols urinary metabolites. The greatest contributor to this variability was regularly using an attached garage (14%). Use of a gas stove, frying, smoking and vaping in the home contributed to 5% of the variability within the summed PHE urinary metabolites, 3% of which was explained by smoking and vaping. Smoking and vaping in the home contributed the greatest amount of variability (14%) in summed FLU urinary metabolites (13.9%) and 1-PYR urinary metabolites (5%). Eating fried, roasted, grilled, smoked, or barbequed yesterday was not associated with urinary PAH metabolites.

Previous work found that 28% of the 204 homes in the study had one smoker and 41% reported burning incense in the house, but did not find evidence of a relationship with environmental tobacco smoke exposure or incense burning.[98] Among non-smokers, prediction models investigated including demographic and housing characteristics, participant-reported food intake, and modeled outdoor air pollution, accounted for only 2-5% of the variability in urinary PAH metabolites.[54]

We find that smoking and vaping are strong predictors of urinary FLU metabolites. Burning candles or incense may contribute to urinary FLU metabolites; however, we were not able to assess that contribution due to the low prevalence of incense and candle use in the study population. We were not able to detect significant predictors of urinary PHE or PYR metabolites; however, there appear to be various predictors of urinary naphthols metabolites, the most significant being regularly parking in an attached garage. Burning candles and smoking are predictors of airborne PYR, but we did not see urinary PYR related to burning candles or smoking.

In our analysis, the upper half of children's metabolite concentrations are higher than adults within the same household, shown by the fact that the medians of the child/adult ratios are approximately 1 and the arithmetic means of the child/adult ratios are greater than one. Participating home 174, 146 and 103 had the highest child/adult ratios for 1-NAP metabolite concentrations, pointing to possible participant-specific exposures rather than household-specific exposures, or differences in metabolism or excretion between adults and children, which is well-established in the literature. In participating home 103, where the child’s urinary 1-NAP metabolites were the highest among the study population, candles were burned, the oven and stove were used, windows were opened, and both the adult and child participants ate baked chicken. In participating home 146, smoking and vaping occurred in the home, and the child was reported to have eaten fried cheese sticks and French fries while the adult participant did not eat any fried food. In participating home 174, the oven and stove were used multiple times, and windows were opened frequently, however, neither adult nor child ate fried food. High variability in individual metabolism and excretion of PAHs may contribute to these results.

In an analysis of 2003-2008 NHANES data, women had statistically significantly higher urinary metabolites for 1-NAP, 2-NAP, 1-PHE and 1-PYR compared to men.[90] The participants in our study were predominantly female-identifying, and we were not able to investigate gender differences. Previous studies also found higher concentrations of PAH metabolites among non-Hispanic, white participants and the lowest concentrations among Mexican American participants, with the exception of the 2-NAP metabolite specifically, which was highest among Mexican Americans. We did not find similar differences by race/ethnicity in our study population.

2.4.8 Limitations

Limitations of this study include the cross-sectional nature of this investigation, which does not allow for temporal or causal inference. We could not measure outdoor samples on three occasions when we collected indoor samples at homes due to rainy weather or there not being a safe outdoor place to store the air sampling equipment. Additionally, two indoor air samples were lost due to turning the air sampling equipment off at night upon the request of the participants due to noise. The winter season, known to result in higher PAH concentrations, was not characterized in this investigation due to a delay in receiving the funding to initiate this study. GC/MS instrument error resulted in a high LOD for airborne PAH samples. Substitution of values below the LOD by calculating the LOD divided by square root of two is a commonly used method for left-censored data; however, doing so may bias parameter estimation and result in lower variability in the data.[49] Although adjusting for specific gravity of urine is commonly performed and thought to be more accurate than creatinine adjustment, there is some evidence that sociodemographic factors, as well as gender, race/ethnicity, body mass index, height, age and time of collection may also be underlying reasons for differing specific gravity values.[61] The small sample size of our investigation (64 homes) resulted in a lack of power to detect statistically significant differences. Additionally, some variables were relatively homogenous; for example, use of home heating, incense use, and smoking. Other sources of PAH exposure which were not included in survey instruments, were the use of moth balls, which often contain NAP, as well as occupational exposures.

Pairing indoor and outdoor air samples at residences represented a more accurate form of exposure assessment than solely outdoor measurements, which have been more commonly used to inform residential exposures. Still, personal samples would have been even more illustrative of personal air exposures potentially impacting urinary PAH metabolite concentrations and the impact of cooking-related exposures. The analysis of 1-NAP in urine only yielded 51% detectable samples, possibly due an analytical interference based on the sulfatase activity from the beta-glucuronidase enzyme used to release the free hydroxylated metabolites.[100]

Very few participants responded that they cooked in their home, used cleaning products, or used personal care products “yesterday”, which was the day that the air sampling started in their home; however, there was a logical distribution of those same participants reporting that they did those activities "today", or the day that the air sampling ended in their home and when these questions were asked. Although many participants reported cooking "today", which would have been after the urine samples were collected (during the first morning void that day), there were no participants that reported cooking "yesterday", during the first half of the study period. Due to the short half-life of PAH metabolites, which are thought to circulate in the body for 3-10 hours before being excreted, exposures during the first half of the study period had the potential to show up in the urine samples, however any exposure during the second half "today" would not. Additionally, PAH air samples captured integrated airborne PAH concentrations for a few hours after the urine samples were collected on day 2 of the sampling period. In spite of these limitations, this characterization of residential exposure to PAHs fills a gap in understanding sources of residential exposure to PAHs in communities that have historically been burdened by excess air pollutant exposures.

2.4.9 Implications

Many exposure estimates of PAHs are based on ambient measurements collected outdoors. This investigation provides a more holistic look at various sources of exposure based on the collection of indoor air samples as well as outdoor samples at homes. Urinary metabolites offer additional insight about exposure sources. Accurate information about exposure sources can inform methods of exposure reduction.

Outdoor measurements were significantly associated with indoor measurements and we found evidence of infiltration. Consistent with findings from Noth et al. in Fresno over the last twenty years, reducing outdoor PAH air pollution is protective indoor exposures. Although there are known indoor sources of PAHs including cooking, burning candles, incense, and wood, home heating, some home product use, we found home heating with a gas-powered furnace to be the only variable that was significantly associated with an increase in all four PAH air concentrations. We could not detect an effect of air filters and few participants in this study population used them, however other studies illustrate protective effects of reduced indoor air pollution due to air filtration use. Three of the four PAHs in this study (all except PYR) are primarily in the vapor phase and would not be reduced by use of an air filter.

Occupational studies have reported that airborne NAP concentrations are highly correlated with summed total PAHs. [85,101] We found that airborne NAP was not correlated with the summed total of the other three PAHs, possibly because NAP concentrations were significantly higher than other compounds. This indicates that NAP cannot be used as a surrogate of exposure to other PAHs, and that the two separate methods to measure NAP and other particle-phase PAHs is worthwhile for future exposure assessment.

Cooking is a known source of PAH exposure and epidemiological studies have shown associations between cooking fumes and respiratory disease, cardiovascular disease and cancer.[102] Although 95% of participants reported having an exhaust hood or vent fan in their kitchen, and 90% initially reported using it sometimes or all the time during cooking, only 26% of participants reported using while cooking during the 24-hour sampling period. We found evidence of cooking-related exposures, particularly frying and barbequing; PAH emissions during these high-temperature cooking activities have been previously reported. Education on the use of vent fans and incorporating kitchen vent fans into all building codes may be warranted to reduce.

Our findings suggest that gas-powered heating is a significant source of exposure to PAHs. Moratoria on the development of gas appliances in new buildings in some cities (i.e., Berkeley) and the increased availability of renewable energy to power electric appliances will decrease these exposures over time. Residential wood-burning remains a significant source of PAH air pollution in the winter in many California counties, including the San Joaquin Valley.

Smoking and vaping in a few participating households resulted in evidence of exposure to adults and children in those homes. For children, and adults who passively were exposed, this is a preventable source of exposure and education is needed to for parents on the harmful impact of smoking and vaping both tobacco and cannabis indoors. Even third hand exposure from a family member who smoked outside of the home resulted in increased cotinine exposure for one participant; smoking outside is very helpful in reducing exposure, but it does not eliminate exposure. Education for parents about indoor smoking and vaping, third-hand smoke, as well as burning candles and incense could help families reduce exposures to PAHs.

Our summed NAP metabolite results are higher than those measured among children ages 6-17 in the most recent iteration of the National Health and Nutrition Examination Survey (NHANES), which measured urinary 1-NAP and 2-NAP among a representative random sample of the population, indicating potential disproportionate exposure (Table S3).[103]

2.5 Conclusion

Measured airborne PAH concentrations were lower than previously measured values reported elsewhere. Seasonal effects were observed, with higher sample concentrations collected in the spring. We found evidence of infiltration of outdoor concentrations into home environments, which may have been facilitated by opening windows and by home type. Frequently opening windows significantly increased the effect of outdoor NAP and FLU concentrations infiltrating indoors. There is limited evidence that mobile homes may result in higher infiltration of outdoor PAHs. Traffic volume and regularly using the attached garage were significant predictors of FLU concentrations. Burning candles in the home during the study period was significantly associated with higher indoor PYR concentrations. Using gas-powered heat was significantly associated with indoor concentrations of FLU and PHE. NAP was significantly associated with gas-powered heat use in a bivariate relationship, but became insignificant when adjusting for outdoor NAP concentration and season. We found no association between air concentrations and urinary metabolites, suggesting that other sources of PAHs contribute to urinary metabolite concentrations. Participants who smoked or vaped in the home had significantly higher urinary FLU, PHE and PYR metabolite concentrations. Our results show some evidence that urinary metabolites are higher among active smokers versus participants exposed to second-hand or third-hand smoke. More research is needed to understand the various drivers of urinary metabolite concentrations.

Chapter 3. Engaging Farmworkers and Agricultural Employers: An Exploration of Attitudes about Work and Diesel Exhaust

3.1 Introduction

Farmworkers often experience cumulative impacts including social stressors, health disparities, and environmental hazards associated with their work or living conditions. Approximately 50% of farmworkers in this country do not have authorization to work in the United States. There has thus been a dearth of accurate information about the health status of this population.[104,105] Nevertheless, there is evidence of health disparities among farmworkers reported in national surveys and studies.[106,107] It was reported in 2022 from the University of California, Merced, that between one third and one half of farmworkers expressed having at least one chronic health condition, which included diabetes, hypertension, anxiety, depression, and asthma.[30] Forty three percent of survey respondents from this study would be considered obese based on self-reported height and weight data.

Farmworkers also face unique social and psychological stressors related to job security, immigration status, financial challenges and poverty, social isolation, and inequitable access to resources such as health insurance, high-quality housing, and transportation.[31,32,33] The National Agricultural Worker Survey (NAWS) found that US-born farmworkers have more secure work, less onerous tasks, and are paid more per hour than undocumented workers.[108] For at least four decades, researchers have been documenting the mental health stressors associated with farm work, including increased depression, anxiety, and suicide. The lives of immigrant farmworkers are marked by many structural vulnerabilities that likely contribute to chronic stress and heightened rates of depression.[109] Additionally, control over work has been consistently found to predict health status.[37] Working a high demand job is associated with elevated risk for cardiovascular disease, negative pregnancy outcomes and increased psychosomatic complaints.[111] Having some amount of control over one's job tasks or exposures can buffer the negative impacts of high job demand.[112]

Farmworkers may also experience disproportionate environmental exposure burdens related to their work, including exposure to pesticides, herbicides, heat, and dust. In addition to these, diesel exhaust presents a significant, yet often overlooked hazard. Compliance exposure monitoring in occupational settings is conducted for hazards with established regulatory exposure limits.[113] Diesel exhaust is classified as a carcinogen, however, with the exception of the mining industry, there are no occupational exposure limits for diesel exhaust in other sectors. There have been exposure assessments and epidemiologic investigations among some occupational cohorts, including miners, truck drivers, and railroad workers, to establish the finding that diesel exhaust is a carcinogen.[114–116] Diesel exhaust exposure is prevalent in many workplaces, and other occupational cohorts remain understudied, including farmworkers.[117]

Between 1991 and 2007, thirteen studies measured diesel exhaust exposures as elemental carbon (EC) among workers using off-road diesel equipment in outdoor settings. These studies found geometric mean concentrations ranged from 200 – 6,600 ng/m^3 and arithmetic means from 400 –

122,000 ng/m^3.[117] Six of these studies reported EC concentrations that approach or exceed the proposed Threshold Limit Value (TLV) (20,000 ng/m^3) recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) based on review of scientific literature.[118] Although this TLV was not formalized, and was withdrawn from further review in 2003, these exposures approaching or exceeding the proposed TLV indicate a possible health risk for workers in occupational environments working with off-road diesel engines. Even moderate exposure concentrations below the proposed TLV among truck drivers resulted in a 1-2% excess lung cancer risk above the background risk of 5%, after adjusting for smoking.[119] The burden of excess lung cancer cases attributable to occupational diesel exhaust exposure between 1961 and 2001 in Canada was estimated to be 2.4%, which included workers in low- to high-exposure jobs.[120] Researchers have recently found diesel exhaust exposure among miners to be associated with excess mortality due to other cancers of the respiratory system and Non-Hodgkin lymphoma.[121]

Only one study to our knowledge investigated EC in off-road diesel exhaust among agricultural workers in which, modeled exposure estimates based on minimal historical data ranged between 100-400 ng/m^3.[122] There is a large variability in diesel exhaust emitted among different types of off-road equipment as well as the work tasks farmworkers conduct affecting their exposures. There was a lack of detail regarding the historical exposure scenarios, suggesting that these exposures reported may not be meaningful without work task data.

The Agricultural Off-Road Diesel Exposure (ACRE) Pilot Study intended to address gaps in understanding farmworker's exposures to diesel exhaust as well as their attitudes about work conditions, wellbeing, and their returned study results. Results from the ACRE Pilot Study are presented in Chapters 3, 4 and 5 of this dissertation. The ACRE Pilot Study was funded by a pilot study grant from the California Labor Lab in 2023. It was aligned with the National Institute of Occupational Safety and Health (NIOSH)'s *Total Worker Health* framework. NIOSH defines the *Total Worker Health* Approach as policies, programs and practices that integrate protection from work-related safety and health hazards with promotion of injury and illness-prevention efforts to advance worker well-being.[123]

This chapter describes results from participant interviews conducted in the ACRE Pilot Study. Chapter 4 reports on the personal exposures to diesel exhaust pollutants among farmworkers, which prior to this study, had not been well-characterized. Lastly, Chapter 5 describes the development of worker-informed report-back materials and usability-testing interviews to evaluate them.

3.2 Methods

3.2.1 Farm and Farmworker Study Population

We attempted to recruit farms that were representative of farms and labor contractors in California, including organic and non-organic and small to large-sized operations, operations in San Joaquin Valley, which contains over 50% of California's agricultural equipment, and farms growing the most highly produced crops in California: strawberries, grapes, nuts, apples, lettuce, and tomatoes.[7] Recruitment was conducted through word of mouth, attending workshops and conferences, internet research, and connecting with farmer stakeholder organizations such as farmer advocacy organizations, agricultural alliances and research groups, and farmer's market associations. A total of 25 agricultural operations and 6 farm stakeholder organizations were approached to recruit employers. A total of five employers of agricultural operations participated in the pilot study; they grew apples, stone fruit, diversified vegetables, wine grapes, and table grapes in the counties of Mendocino, Yolo, Contra Costa, and Fresno. Four of the five employers owned small- to medium-sized organic farms and one employer was a labor management company.

Farmworkers were recruited at these 5 locations in Northern California where employers granted researchers access. Farmworkers and two farmers on small farms performing work representative of farmworkers (n=29) who consented to participate wore personal exposure monitoring devices to measure three constituents of diesel exhaust for their work shift **(Chapter 4).** Twenty-seven (93%) farmworkers in the study worked on an organic farm. A subset of farmworkers (69%) participated in work-related interviews based on their interest and availability (n = 20). All study protocols were approved by the Institutional Review Board (IRB) at the University of California, Berkeley (Protocol ID 2023-09-16692). The terms farmworker, employee, and participant are used interchangeably.

3.2.2 Interviews Exploring Work Practices and Attitudes of Exposure and Safety

Qualitative semi-structured work interviews were conducted to explore participants' attitudes about diesel exhaust exposure, work tasks, occupational health and safety, whether participants wanted to receive their study results, and if so, what they hoped to learn. Items from the validated Perceived Stress Scale and Migrant Farmworker Stress Inventory were included in the semi-structured interview guide.[109,124] Participant interviews informed how best to return individual study results to participants who elected to receive them. The interview guide was translated to Spanish and tested with Spanish-speaking and farmworker populations prior to deployment in the field. Most participants chose to be interviewed at their work site, with some requesting interviews at their home or at a public park.

3.2.3 Rapid Qualitative Analysis of Interview Data

Interview data was analyzed via Rapid Qualitative Analysis (RQA), as described by Hamilton and Finley and evaluated by Taylor et al.[125,126] According to rigorous best practices of RQA, qualitative data from participant interviews was deductively compiled into structured templates that were pre-determined based on interview guide items. Two different research analysts analyzed work interview data to establish reliability of the data analysis and validity of the emerging themes. Due to resource constraints, one researcher analyzed the interview data from the report-back usability testing interviews.

3.2.4 Report-Back of Study Results

Upon conclusion of the study, employers were offered study results including farm-level and tractor-specific data. Farmworkers were asked during the informed consent process if they wanted to receive their study results. Work interviews informed the content of report-back materials. A subset of the twenty farmworkers who participated in interviews were randomly recruited via phone calls and text messages to evaluate the usability, accessibility, and understandability of study results. Participants who responded participated in usability testing interviews (n=8) **(Chapter 5).** After receiving feedback and performing iterative updates on report-back materials, report-back materials were sent to all farmworkers who elected to receive them.

3.3 Results

In addition to being asked about demographic and employment information (**Table 1**), farmworkers (n=20) were interviewed about what they liked and disliked about their work, their tasks performed at work, their perceived job demand, job autonomy, and job stress, awareness of health and safety practices at work, and their attitudes about diesel exhaust exposure, and receiving their exposure monitoring results. Quotes were included in the original language of the participant. Quotes in Spanish were translated to English. Additionally, participants are referred to using gender-neutral pronouns to keep their information as confidential as possible.

Table 1. Participant Information

Demographic & Employment Characteristics		**Number of Participants**	**(Percent)**
Gender	Male	14	(70%)
	Female	6	(30%)
Race/Ethnicity	Latino/a	18	(90%)
	White	1	(5%)
	Asian	1	(5%)
Country of Origin	Mexico	10	(50%)
	Guatemala	2	(20%)
	Honduras	6	(30%)
	United States	2	(10%)
Age	21 - 30	6	(30%)
	31 - 40	6	(30%)
	41 - 50	3	(15%)
	51 - 75	5	(25%)
Years worked for current employer	0 - 5	12	(60%)
	6 - 11	4	(20%)
	12 - 17	2	(10%)
	50 - 55	2	(10%)
Primary Language	Spanish	18	(90%)
	English	2	(10%)
Job Title	Farmworker	17	(85%)
	Farmworker & Manager	1	(5%)
	Farmworker & Farm Owner	2	(10%)

When asked about their work, farmworkers expressed a deep connection to working in agriculture and growing food. Five people (25%) said they liked working outside in the fresh air, 6 people (30%) said they liked working with plants or growing food, and 6 others expressed a combination of reasons they liked working in agriculture, including those stated above and learning new things.

> *"…me gustan las plantas, verlas crecer, hasta que dan en fruto, me gusta todo el proceso, desde que las plantamos hasta que las cosechan y paquetearlas. Lo que no me gusta es andar en el sol."*
>
>> *"I like plants, watching them grow, until they bear fruit, I like the whole process, from planting them to harvesting and packing them. What I don't like is working out in the sun."*

> *"I wanted to be specifically an organic farmer because I want the next generation to not die from different things we're poisoning our land with. I guess it's in my blood, I don't know, my grandpa did it, my dad did it."*

Along with the benefits of working in Mother Nature comes unpredictable weather. Most participants reported having to work in bad weather, including heat, rain, or wildfire smoke (16 out of 20, or 80%). Many people expressed feelings that working in hot temperatures or rain is to be expected with agricultural work. Three people were grateful that their employer required employees to stop work during extreme heat, while seven others (35%) expressed that it was stressful to have smaller pay checks because of shortened workdays during periods of extreme heat.

> *"Hay veces que no sentía calor y paramos pues, por la ley, y hay veces que hay demasiado calor y no paramos pues…. Cuando nos paran, es menos dinero pues, menos horas…. Es difícil porque hay menos dinero."*
>
>> *"Sometimes I didn't feel hot, and we stopped anyway, because of the law, and other times it's really hot and we don't stop. When they make us stop, it's less money, fewer hours…. It's hard because there's less money."*

> *"Cuando ya hace mucho calor es mejor descansar que tal desmayarse uno."*
>
>> *"When it's really hot, it's better to rest than to risk fainting."*

Other sources of job stress that participants expressed included long commute hours, long hours at work, seasonally high job demand during harvest, and relationships with superiors or subordinates. People with longer commutes to work expressed a greater amount of stress. Eleven people (55%) drove 15-30 minutes one-way to get to work, 4 (20%) people drove 45 minutes one-way, and 2 people (10%) drove one hour one-way. Three people lived at their respective farms. Many participants reported the seasonal nature of their job demand, and how job stress fluctuates throughout the year.

> *"En realidad, vivo más en el trabajo que allá. Solo llego a descansar, y ya otro día otra vez… como digo, 45 minutos en la mañana, entramos a las 5:00, a las 4:00 salir de allá…"*
>
> > *"Actually, I spend more time at work than at home. I only go home to rest, and then it's another day again… like I said, 45 minutes in the morning [driving to work], we start work at 5:00 am, so I leave home at 4:00 am…."*

> *"Es estresante en el aspecto que tengo que estar muchas horas allí, en vez de... quisiera dedicar tiempo a mi familia, pero como sé que es solo por un tiempo, a mí me parece bien, no es todo el tiempo."*
>
> > *"It's stressful in the aspect that I have to be at work for many hours, instead of… I would like to dedicate time to my family, but I know it's only for this time period, I'm okay with it, it's not all the time."*

Two of the participating farmworkers worked for a labor contractor, two were farm owners doing equivalent work of farmworkers on small farms, while the remaining 16 participating farmworkers worked directly for their employer on a full-time or seasonal basis. Twelve people (60%) expressed during the interviews that they had stable work or year-round employment. Overall, nineteen people (95%) expressed low or medium job stress, while only one person reported high job stress due to managing a crew with high job demand, and not feeling adequately compensated for their responsibilities. Another employee reported overall low job stress at work, but similarly felt that driving a tractor and managing a crew was stressful due to the amount or produce they had to harvest each day.

> *"Voy a veces en el tractor me bajo a piscar, trabajar con ellos cuadrilla porque necesito sacar lo me están pidiendo. Y cuando ya saco lo que me están pidiendo, ya estoy tranquilo…. Siempre tengo que voy enseñando a la cuadrilla la calidad del producto y como se piscar. Es una responsabilidad…. Imagínate son como 17 años trabajando en el rancho, creo que no es ilícito, no es conveniente ganar un dólar más de los piscadores. Aparte de eso, cargo una responsabilidad con el tractor. Si yo lastimo a alguien con el tractor, va sobre mí la regañada. Si el producto no va bien, me llaman la atención a mí. Por eso es una responsabilidad. Por un dólar, no vale la pena."*

"Sometimes I drive the tractor, and I get off to pick, to work with them [the crew] because I need to pick what they're asking of me. And when I harvest [the amount of produce] that they ask for, I feel at ease…. I always have to teach the crew the quality of the produce [to harvest] and how to pick it. It's a responsibility…. Imagine, I've been working at this farm for 17 years, I don't think it's right, it's not fair to earn one dollar more per hour than pickers. Apart from that, I have the responsibility with the tractor. If I hurt someone with the tractor, I'm the one who gets reprimanded. If the produce we pick isn't good [or enough], they call me out for it. That's why it's a responsibility. For one dollar more, it's not worth it."

Experience of knowing the job and working there for many years reduced feelings of job stress that they felt earlier on in their work there.

"Ahorita, como uno ya sabe todo, [el trabajo] no es estresante."

"Now that I know how to do everything, work isn't stressful."

One participant expressed not feeling supported by management and having to provide their own work gloves, which felt like a source of stress in combination with the productivity demands. They said that when they worked at other farms for a labor contractor, workers were provided with face masks and he would have liked to receive face masks, gloves, and safety glasses. On the day of the work interview, they had gotten a bee sting on their hand, which the researcher performing the interview observed to be very swollen; their hand would no longer fit into their glove. They said during the interview that they let their manager know that it was very swollen and painful, and was not offered medication or first aid supplies. They felt that their manager implied they should keep working and that paid time-off was not an option.

Questions about participants' access to healthcare were asked in some interviews and omitted in others due to it being a sensitive question. Among the 11 participants who were asked explicitly about this, six participants expressed feeling able to access healthcare: some people had health insurance through work, and others without work-related insurance felt they could access emergency healthcare services if needed. One person reported that it was too expensive to receive health insurance through work, so it was declined. Two employees mentioned back and knee injuries from their work, but the majority of people (65%) reported never receiving injuries at work beyond headaches or bee stings.

Participants were asked if they received health and safety training at work and if they could suggest ways to protect farmworkers on the job. Most participants (90%) expressed awareness of at least one example of health and safety practices at work. Thirteen people (65%) cited examples related to heat stress prevention including drinking water or taking breaks in the shade. Other people mentioned the following health and safety examples, some of which were mentioned in addition to heat stress prevention: personal protective equipment (20%) such as Tyvek coveralls, safety glasses, gloves or respiratory protection such as face masks or a powered air-purifying respirator (PAPR), pesticide awareness (15%) in regards to pesticide spraying on neighboring farms or because it is generally used in agriculture, even though all participating farms were organic, tractor safety (10%) such as using proper gears and breaks, wearing a seat belt, and being cautious of other people, not working or using masks during wildfire events (10%), having access to clean bathrooms and hand washing facilities (5%), ladder safety (5%), and cardiopulmonary resuscitation (CPR) knowledge (5%).

All participants in the study were observed by researchers as having access to bathrooms, as well as drinking water and shade during hot temperatures. No participants were observed wearing filtering facepiece respirator masks, though one participant used a PAPR to protect from dust inhalation. Many participants wore bandanas to protect from exposure to dirt, dust, and the sun. The high level of awareness of heat stress prevention among 65% of participants indicates widespread training and awareness on the farms in this study. Many participants (65%) also expressed receiving some type of health and safety training from their current employer. Employees reported receiving training in tractor safety and heat illness prevention.

When asked about their perception of diesel exhaust, half of participants (10 out of 20) said they had never thought about it before or did not really notice it. The other half of participants expressed smelling it or having a general awareness of it. Among them, 8 people (40% of all participants) were specifically concerned about exposure for health reasons, particularly long-term exposure. Six people reported noticing the diesel exhaust smell while working near tractors; four of them felt it was bothersome and reported getting headaches, coughing, or feeling ill after smelling it. One person in particular reported getting headaches after driving the tractor because of the smell of the exhaust and the noise and heat from the tractor.

> *"A veces si, se siente bien fuerte cuando inhalamos. A veces lo hace toser a uno."*
>
> > *“Sometimes, yes, it feels intense when we inhale it. Sometimes it makes you cough.”*

> *“…No sé qué consecuencias tenga al largo plazo o corto plazo, pero me imagino que enfermedades de la respiración o los pulmones… después de muchas horas de exposición."*
>
> > *“I don’t know what kind of long-term or short-term consequences it can have, but I imagine respiratory or lung diseases… after many hours of exposure.”*

Participants expressed implicit awareness of exposure reduction methods when describing their exposure experience and the degree to which they felt concerned about diesel exhaust. One person expressed concern about the frequency of their exposure.

"Podemos pensar que un solo tractor no puede afectar tanto, pero es un tractor… que se usa todos los días. Creo que yo paso más tiempo en un tractor que durmiendo en un día, así que es bastante la contaminación."

> *"We can think that just a single tractor can't affect someone that much, but it's a tractor that… you use every day. I think I spend more time on a tractor than sleeping in a day, so there is a lot of pollution."*

Others said they were not concerned about diesel exhaust because of the infrequency of their work around tractors (4 people), the distance they work from tractors (3 people) and the short duration of exposure (1 person).

"Si estuve olido todos los días, tuviera más mal."

> *"If I smelled it every day, it would be worse."*

Two people reported that they had noticed a difference in the amount of diesel exhaust they inhaled or smelled with the distance they were from the tractor depending on the type of crop they harvested. Additionally, two people felt protected from diesel exhaust exposure by the closed cab of the tractor and two others expressed that well-maintained tractors produce less exhaust. Lastly, two participants noticed a difference in the amount of diesel exhaust they were exposed to with different tractors they used, based on the location of the tailpipes.

When asked specifically about their knowledge of reducing or avoiding exposure to diesel exhaust, 15 participants overall (75%) expressed awareness of one or more factors that could increase or decrease exposure to diesel exhaust. These ideas included maintenance of tractor engines (8 people), the age of the tractor or using newer tractors (5 people), respiratory protection (5 people), the amount of time working near tractors (6 people), distance from tractors (5 people), acceleration of tractors while driving (1 person), and filters on the tailpipe (1 person).

"Uno no puede resistir mucho humo que está pegando la cara. Cuando el cuerpo de uno siente que el aire del tractor se afecte, entonces, mejor que apartes o alejas… mejor retirarse."

> *"You can't withstand a lot of smoke that's hitting your face. When you feel the tractor exhaust affecting you, then it's best to move away… it's best to take a break."*

Five people didn't know how to reduce their exposure, with one person suggesting that not using diesel-powered tractors would be the only thing they could think of. Three people (15%) additionally expressed awareness that diesel exhaust can harm the environment or contribute to climate change because of the impact on regional air pollution. Four participating employers in this study operated organic farms. Three participants (15%) expressed gratitude that they worked on organic farms and did not have to work with chemicals.

> *"Pues aquí no usa químicos, o sea químicos naturales, no les hacen daño, pero si en otros ranchos."*
>
> > *"Here we don't use chemicals, but we use natural chemicals, they don't harm you, but at other farms, they do use chemicals."*

In addition to being asked during the consent process if they would like to receive their personal exposure monitoring results, participants were also asked during interviews, including what they would like to learn from their results. During the consent process, 26 participants (89%) said they would like to receive their personal exposure monitoring results. Among the participants who were interviewed, most participants (18 out of 20, or 90%) also wanted to receive their results. The two people that did not want their results saw no benefit of receiving them, and one person mentioned not knowing what they would learn from them. People were primarily motivated to receive their results because they were curious how much diesel exhaust, they were exposed to, or if their exposure would be considered elevated (45%) and whether the exposure could affect their health (30%).

> *"Aprender de lo que podemos prevenir y lo que no podemos prevenir…Sabiendo de que... cuanto afectaría nuestra salud con el trabajo que hacemos, y tanto el humo de la máquina, entonces pudiéramos aprender cómo evitarlo…"*
>
> > *"To learn what we can prevent and what we can't… knowing how much our health would be affected by the work we do and by the smoke from the tractor, then we could learn to avoid it."*

Two people also wanted to understand what the results meant in the context of the study and what the study results were overall. Eight people (40%) expressed not knowing what to expect from their results, but most of them still wanted to receive the results, with one person specifically saying they thought they would not understand them.

> *"La información que me pueden mandar, para saber no más. Yo no sé lo qué van a decir… porque yo no lo voy a entender."*
>
> > *"Whatever information you can send me, just to know. I don't know what it will say… because I'm not going to understand it."*

When asked how participants would like to receive their results most people requested them via hard copy in the mail, with a few requesting electronic copies via email or via text.

Employers were asked if they were aware of programs to fund the replacement of older diesel-powered tractors, and 80% (4 out of 5) were unaware of programs to fund newer diesel-powered tractors with lower emissions or electric agricultural equipment.

3.4 Discussion

Work interviews with participants in this study explored the context of farmworker demographics and work conditions to provide important information about work practices, awareness of health and safety, and attitudes of exposure, all of which informed report-back strategies and exposure reduction recommendations. Farmworkers generally face numerous environmental health hazards at work as well as a disproportionate burden of health disparities and social stressors.[127] The farmworkers in this study population expressed a high degree of satisfaction about their employment and general wellbeing at work. The working conditions among participants in this study may not be generalizable to the larger farmworker population in California or the United States because 93% of participants in this study worked on organic small to medium-sized farms. Sixty percent of interviewed participants expressed that they had stable work or year-round employment and 95% expressed low or medium job stress. Still, major contributors to stressful working conditions among those interviewed included high job demand (pressure for high productivity), long commute or work hours, and financial stress. The Job Demand-Control Model, a leading theory about job stress, describes how low job control and high job demand interact to increase job stress, which has been associated with adverse physical and mental health outcomes impacting immune function, cardiovascular health, and psychosocial wellbeing.[112] Many participants expressed medium to low job control, or a small to moderate amount of control over how they do their work, which if paired with high job demand, could limit their own sense of agency to reduce exposures or work conditions either alone or in collaboration with their employer.

The specific crops grown on these farms, the size of the farms, and the nature of organic farming likely resulted in work tasks at these farms that were generally more labor intensive than other agricultural operations in the country, for example corn, soy, or wheat. A significant attempt was made to recruit farms in the San Joaquin Valley because it contains over 50% of California's agricultural equipment;[7] however, we able to recruit only one participating farm from this region. Additionally, it was important to get buy in from employers to prevent any employer retaliation among participating employees; however participating employers may not be representative. Although participating farms and farmworkers in this study population may not be representative of the state or the United States, their measured diesel exhaust exposures are likely generalizable among farmworkers in the country working with similar crops. Diesel-powered agricultural equipment is ubiquitous in agriculture, and exposure has remained relatively invisible because associated health effects are often delayed, varied, or undocumented.[128]

Diesel exhaust is composed of many chemicals and working with tractors presents an inhalation risk for farmworkers, yet many farmworkers interviewed were not aware of this exposure risk.

About half of participants interviewed expressed previous awareness or concern about diesel exhaust. Awareness was expressed equally among farmworkers who drove tractors and those who did not. However, concern about exposure was expressed among tractor drivers because of the increased frequency of their exposure compared to other farmworkers who are not next to the tractor every day. Concern about exposure was thus driven by frequency and duration of exposure. The degree to which participants felt concerned may also be influenced by prior awareness of the exposure and the ability to mitigate one's exposure. For example, two participants expressed a prior awareness of diesel exhaust exposure and working in a way that would create more distance from the tractor tailpipe or using personal protective equipment to reduce their exposure. These examples of individual-level actions reflect control over their own ability to protect themselves. Participants also expressed increased concern about health risks that might be associated with long-term exposure over many years. The idea that concern can arise from feeling a lack of control or uncertainty in how long an exposure will continue based on job precarity or little control over employment trajectory is consistent with the Job Demand-Control Model. Similarly, having some amount of control over one's job tasks or exposures can buffer the negative impacts of high job demand.[112]

Fifteen percent of participants interviewed expressed gratitude that they worked on organic farms and did not have to work with chemicals. Another participant who was not officially interviewed due to scheduling difficulties referenced the many chemical exposures that he experienced when working in Mexico in the past and appreciated not working with them in California. Although many people may not consider diesel exhaust as a chemical exposure, it contains thousands of airborne chemicals, some of which are associated with cancer and other adverse health outcomes. Furthermore, the California Occupational Safety and Health Administration's Hazard Communication Standard requires that employers provide warnings or trainings to workers if chemicals listed in Proposition 65, which cause cancer or reproductive toxicity, are found in their workplace.[129] Diesel exhaust is a listed as a Proposition 65 chemical, thus training for farmworkers is warranted.

Many participants (75%) expressed intuitive ideas about reducing their exposure, including distancing oneself from the tractor (or specifically the tailpipe), or spending less time around a running tractor when possible. In the prepared report-back materials, we recommended exposure reduction strategies based on the hierarchy of controls; this framework seeks to control occupational hazards in order of the most effective, high-level actions to reduce exposures for many, to the least effective individual-level actions.[130]

Most participants wanted to receive their personal exposure results: 89% of the 29 participants in the diesel exhaust air monitoring study, which reflected 90% of the participants interviewed. This information is consistent with other studies, demonstrating that participants of environmental health studies want access to their results.[37] Given that participants have a right to know about their personal exposure results, researchers have a responsibility to thoughtfully return results that are meaningful and appropriate for the study population.[131] Our efforts to develop participant-informed report-back that is understandable, accessible and usable for participants highlights the role of report-back in building engagement and EHL among study participants. Even with the fact that 5 out of the 8 participants of report-back usability testing interviews expressed concerns about their exposure to diesel exhaust or uncertainty about chronic health effects, all eight participants expressed gratitude for the information presented in the report-back document.

Some workers may have been hesitant to share complaints or concerns with researchers during interviews because they were being recorded for Rapid Qualitative Analysis (RQA) or because they were concerned that information might get shared with their employer. RQA has become a widely-used method; it does not require transcription, but instead bases analysis on audio recordings. Traditional qualitative approaches, such as grounded theory, require extensive training, are time- and labor-intensive, often require expensive data management software and transcription fees, and may not be well-suited to address timely health equity issues or exposure reduction efforts.[132] RQA was an appropriate method for the context of this pilot study because they were aligned with our aim to develop a preliminary understanding of a situation from the insider's perspective.[133]

Our finding that many interviewed participants expressed feelings that working in hot temperatures is to be expected with agricultural work, and didn't want to stop work during heat because of lost wages highlights the need for a larger safety net for both farmworkers and small farmers. Similar sentiments were expressed among interviewed farmworkers in an investigation in Idaho.[134] This indicates that the occupational hazards and psychosocial stressors in this study population in Northern California are also experienced by other farmworkers in the United States, underscoring a need for large-scale farmworker protections. The United States Department of Agriculture's (USDA) Economic Research Service estimated that between 52% and 85% of small family farms, depending on farm type, have profit margins less than 10%, which is considered "high-risk".[135] The Community Alliance for Family Farmers (CAFF) recommended policy priorities in 2024, which included equitable access to capital and infrastructure and access to business viability technical assistance and resources.[136] If farmers are supported, they can provide more support to their employees. Additionally, government financial assistance (i.e., disaster pay) for farmworkers who are required to stop work due to extreme weather, including hot temperatures, rain, or wildfire events, may be warranted.

Government programs that provide resources to farmers for environmental health improvements include the California Air Resources Board (CARB) Funding Agricultural Replacement Measures for Emissions Reductions (FARMER) program and the USDA On-Farm Energy Initiative, Equipment Grants Program, and Regenerative Agriculture Pilot Program. Additionally, non-profit organizations and a private energy company in Northern California provide grants to fund electric equipment or sustainable agriculture initiatives. No farmworkers interviewed in this study and only one of the five farmers participating in this study knew about these resources. Many other farmers we spoke to while researching and recruiting for this study were unaware of these support programs as well. After reporting back to farmers about study results, most farmers elected not to take advantage of programs that provide 50% to 100% of the cost of a new tractor because of the administrative burden required to apply for this funding, including providing 2 years of equipment maintenance, usage, and insurance records, proof of ownership, a dated and itemized quote for a new tractor with CARB-approved emissions reductions technologies, the requirement of destroying the existing tractor being replaced, and other requirements, which may vary slightly by air district.[137]

3.5 Conclusion

Farmworkers were interviewed during personal exposure monitoring for diesel exhaust during typical full-shift farm work. They generally expressed satisfaction with their employment, reporting low to medium work stress (95%) and a high degree of perceived job stability (60%). Still, major contributors to stressful working conditions among those interviewed included high job demand (pressure for high productivity), long commute or work hours, and financial stress. Thirty-five percent of participants expressed feeling a sense of financial stress related to having smaller pay checks because of reduced work hours during hot temperatures, indicating economic precarity. Even among employees with generally supportive and aware employers, most participants (80%) reported having to work in bad weather, including heat, rain, or wildfire smoke, and expressed a sentiment that this is to be expected with agricultural work. Participants wanted to receive their personal exposure results. Although many farmworkers' interviews reported receiving health and safety training related to heat and tractor safety, no one received training or education about diesel exhaust exposure. Participants expressed that they would like more information about diesel exhaust, including methods to protect themselves from exposure. Training is required by employers when exposure to cancer-causing compounds occurs at work, and training on diesel exhaust for farmworkers is warranted. This pilot investigation identified opportunities for exposure reduction among farmworkers, barriers to utilizing the equipment replacement grants among farmers, and effective methods of occupational exposure report-back among farmworkers.

Chapter 4. Assessment of Diesel Exhaust Exposures among Farmworkers in Northern California

4.1 Introduction

Diesel exhaust from off-road equipment accounts for 29 percent of diesel particulate matter emissions in California. Off-road vehicles and equipment, which include forklifts, tractors, haulers and water trucks, are expected to be the single largest contributor of diesel emissions in the state by 2030.[7,8] Due to the heavy-duty nature of this machinery and the engine power needed, tractors and many other agricultural equipment are predominantly diesel-powered. The California Air Resources Board (CARB) estimates that there are 160,000 pieces of diesel-powered equipment in the agricultural sector in the state.[138] Although diesel engines are long-lasting and efficient sources of power, they emit 10,000 to 100,000 times more particles than gasoline engines, dependent on the type and age of the engine.[139] This is thought to be due to the greater organic material content in diesel fuel. Diesel-powered engines also release more nitrogen dioxide and nitrous oxide (together known as NO_x) due to their higher combustion temperature.[140] Various factors influence the specific makeup and magnitude of diesel exhaust concentrations, including fuel characteristics, the use of fuel additives, and engine characteristics, such as electronic fuel injection technology or diesel particulate filters.[140] As a result of an amendment to the Clean Air Act, the U.S. Environmental Protection Agency (EPA) established standards for vehicle exhaust emissions. [6] Tier 1 standards were set in the 1990s, followed by Tier 2, Tier 3, and finally Tier 4 standards to regulate vehicle manufacturers.[7]

Even with increasingly stringent emission standards on engine manufacturers from the U.S. Environmental Protection Agency (EPA) since the mid-1990s, diesel exhaust from agricultural vehicles and equipment represents a significant source of air pollution in the state. A single, older Tier 0 off-road engine has up to 80 times higher emissions per hour compared to a new Tier 4 engine.[143] Older tractors in the Tier 0, Tier 1 and Tier 2 categories make up a third of the agricultural equipment in the state, and contributed 60 percent of the nitrogen dioxide and particulate matter emissions in the California in 2022.[138] Newer engine technology (Tier 4) is known to result in reduced air pollution. Many barriers exist for farmers to purchase new agricultural equipment, including unpredictable weather and varying commodity prices which affect the profit margins of farmers, and high costs of purchasing new agricultural equipment, as well as a lack of knowledge of grant programs and lack of personnel on small- and medium-sized farms to apply for grants, which requires documentation.

CARB passed amendments in the *In-Use Off-Road Diesel-Fueled Fleets Regulation* to begin regulating off-road equipment in construction and other sectors in 2024, mandating phase outs of older engines (Tier 0, Tier 1, and Tier 2) by 2036. This regulation does not apply to off-road diesel equipment in the agricultural sector, though CARB established the Funding Agricultural Reduction Measures for Emission Reductions (FARMER) program in 2018 to fund air pollution reductions efforts for farmers in California. Farmers must apply to grants that are made available by air districts to fund air pollution reductions efforts such as the purchase of a Tier 4 diesel tractor or an electric tractor to replace an older tractor.[138]

Diesel exhaust contains thousands of individual chemicals, but when it is emitted as a whole, it is classified as a cancer-causing compound by the International Agency for Research on Cancer (IARC). Evidence of carcinogenicity due to occupational exposure to diesel exhaust was established predominantly among miners, drivers, rail and road transportation workers. [144,145] Few studies have investigated cancer risks and diesel exhaust exposure among agricultural workers.[146] The Agricultural Health Study investigated health outcomes among farmers in a prospective cohort of over 40,000 participants, finding that daily driving of tractors was associated with increased lung cancer risk.[147] Farmers and farmworkers may be at risk of diesel exhaust exposure at work, however their exposures are not well-characterized.

There is a dearth of information about occupational exposures to nitrogen dioxide, NAP, PHE, and ANT, which are all constituents of diesel exhaust. Only six studies investigating occupational exposures to diesel engine exhaust among workers using off-road diesel equipment in outdoor environments characterized nitrogen dioxide.[117] Research on nitrogen dioxide exposures from diesel exhaust in the railroad industry characterized concentrations of 0.016 - 0.074 ppm among employees who partly or primarily worked outside.[148] Epidemiological research on nitrogen dioxide indicates that chronic occupational exposure to concentrations as low as 0.4 – 0.9 ppm (which are an order of magnitude below the Occupational Safety and Health Administration’s Permissible Exposure Limit) may result in decreased lung function and immunological effects.[19–21] NAP, PHE, and ANT are three of the 16 polycyclic aromatic hydrocarbon (PAH) compounds listed as priority air pollutants by the US EPA.[149] PAHs are often emitted in mixtures, making it difficult to disentangle the human health risk associated with exposure to some compounds individually among humans.[9,52] When they have been measured as mixtures, they have been found to be associated with cancer, metabolic diseases, and liver toxicity. NAP is a low-molecular weight, gaseous PAH emitted in diesel exhaust. The Agency for Toxic Substances and Disease Registry (ATSDR) performed systematic reviews of animal studies to illustrate sufficient evidence of respiratory, immunological, and neurological toxicity associated with NAP exposure.[78] It was also classified as a reasonably anticipated carcinogen by the National Toxicology Program in 2021 and a possible human carcinogen by the US Environmental Protection Agency (EPA) and IARC. Unlike NAP, which is present in the environment primarily in the gaseous phase, PHE and ANT partition between the gaseous phase and the particle-phase. PHE has been associated with liver toxicity and reduced immunological effects in animal studies.[15,13] ANT, which is an isomer of PHE and has a very similar molecular structure, showed increased risk of liver and bladder cancer in male and female rats, as well as kidney, mammary gland, and uterine cancer in female rats specifically, in experimental studies measuring oral exposure, indicating the carcinogenetic potential of this compound.[11]

Due to its formation via incomplete combustion, PAH compounds are readily adsorbed onto BC particles. Given that BC is comprised of carbonaceous particles in the fine and ultrafine size range and formed via combustion, there is overlap of documented adverse health outcomes of BC and fine particulate matter ($PM_{2.5}$) and ultrafine particulate matter, which includes respiratory and cardiovascular adverse outcomes, overall increased morbidity and premature mortality.[22] BC is classified as a possible human carcinogen by IARC and it has been associated with adverse cardiovascular, respiratory and neurological outcomes in epidemiological research.[23] In addition to being associated with adverse health effects, BC also contributes to climate change due to its ability to absorb solar radiation and promote the greenhouse effect.[24] Although BC has not been characterized among farmworkers, it was measured among farmers who drove tractors in two studies in Iowa. As expected, farmers who worked near tractors had higher exposures than farmers who worked farther away from tractors.[150] Driving tractors resulted in the highest task exposure compared to farmers performing other tasks.[146]

Among thirteen studies reviewed by Pronk et al. that measured diesel exhaust exposures as elemental carbon (EC) among workers using off-road diesel equipment in outdoor settings, geometric means results ranged from 200 – 6,600 ng/m^3 and arithmetic means ranged from 400 – 122,000 ng/m^3.[117] Six of these studies reported EC concentrations that approach or exceed the proposed Threshold Limit Value (TLV) (20,000 ng/m^3), which is a recommended threshold established by the American Conference of Governmental Industrial Hygienists (ACGIH) based on review of scientific literature.[118] Although this TLV was not formalized, and was withdrawn from further review in 2003, these exposures approaching or exceeding the proposed TLV indicate a possible health risk for workers in occupational environments working with off-road diesel engines. Elemental carbon (EC) and BC have the same composition, but they are measured differently. EC is a thermally stable form of carbon that is measured via thermal decomposition. BC encompasses light-absorbing carbon particles and is measured optically by light absorbance via a 880 nanometer wavelength laser.[151] EC and BC both constitute a significant fraction of particulate matter mass emitted in diesel exhaust, with estimates ranging from 31-90% based on fuel and engine-type. Aethalometer technology has been used for over 30 years and has been established as a tried-and-true sampling method for BC.[152]

The aims of this investigation were to characterize personal occupational exposures to airborne black carbon, nitrogen dioxide, naphthalene, phenanthrene and anthracene among farmworkers using diesel-powered equipment. To our knowledge, this is the first investigation to quantify these constituents of diesel exhaust among farmworkers via active sampling methods.

4.2 Methods

4.2.1 Study Population Recruitment

Farmers were recruited via phone and email communication and in-person at conferences and workshops. Farms that used diesel-powered agricultural equipment were prioritized for recruitment, including melon, tomato, grape, apple, lettuce, and pumpkin farms. Four farm owners and one agricultural labor contractor consented to participate in the study. We recruited 29 participants via convenience sampling with these 5 employers across 6 farm locations. Farmworkers and farmers or managers that performed similar work tasks as farmworkers were approached to participate in personal air sampling and interviews. Eligibility criteria included working near diesel-powered agricultural equipment during their workday. Participants were enrolled into the study after signing informed consent documents available in English and Spanish. All study protocols were approved by the Institutional Review Board (IRB) at the University of California, Berkeley (Protocol ID 2023-09-16692).

4.2.2 Qualitative Data Collection Methods

In this investigation, we conducted interviews and participant observation in the field to document how and when employees conducted tasks during their workday and their proximity to emission sources. This qualitative data was considered in the analysis of air pollutant data. Participant interview results are reported in Chapter 4. Participant observation is a qualitative research method in which researchers directly observe study participants in their natural environments.[153] In this case, researchers observed farmworkers where they worked, collecting observational field notes throughout the whole work shift for 20 days across the 6 farm locations to develop a deeper understanding of work behaviors and tasks conducted.[153] One intended advantage of this method is that participants become more accustomed to seeing researchers, and thus less likely to change their behavior from what is typical. Researchers showed up at farm locations to talk with farmers and farmworkers prior to starting formal recruitment for personal air monitoring to minimize the Hawthorne Effect, in which participants may change their normal behavior because they are aware of being observed.[154]

4.2.3 Air Sampling Collection Methods

Full-shift (8-hour) and task-based (1-3 hour) sampling was conducted during typical work, and repeated samples were collected on the same participant for up to 4 days. Participants were asked to wear lightweight air monitors contained in a runner's vest during their work shift. These personal samples were collected in the employee's breathing zone to approximate what could be inhaled and are therefore a more accurate assessment of worker exposures than area samples. The duration of samples was intended to be the entire 8-hour shift length; however, some samples were collected for shorter periods of time, such as 2-6 hours, depending on when the work was performed by participants on given sampling days.

Nitrogen dioxide was measured in accordance with the modified OSHA Method 182 via passive diffusion badges containing glass fiber filters treated with triethanolamine (Assay Technology). The passive diffusion rate for nitrogen dioxide is 0.0223 liters per minute (L/min), yielding limits of detection (LOD) based on their analytical limits of quantification are 0.79 ppm for a 15-minute sample, 0.05 ppm for a 4-hour sample, and 0.025 ppm for an 8-hour sample. Naphthalene (NAP), phenanthrene (PHE) and anthracene (ANT) were collected on XAD-2 sorbent tubes at a flow rate of 0.2 Liters per minute (L/min) integrated across full work shifts. XAD-2 is a hydrophobic sorbent that gaseous compounds adsorb onto. Pumps were pre- and post-calibrated in the field to ensure accuracy of total air volume of the sample.

BC was measured with the *microAeth AE51* microaethalometers (Aeth Labs, San Francisco, California) during discrete tasks and averaged over the full-shift. Microaethalometers measure the real-time rate of change in absorption of transmitted light through aerosol deposited on a filter. A small pump inside the instrument pulls air through a spot on the Teflon-coated glass fiber filter at a flow rate of 0.1 L/min. A sampling period of 60 seconds was used because it is more stable with less noise than shorter sampling intervals, but still yields high resolution data.[151,155] A 880 nm light beam passes over the filter to quantify the change in light attenuation due to BC. The absorbance, defined as light attenuation (ATN) of the BC loading on the filter, is measured relative to an adjacent reference portion of the filter once per period, and the gradual accumulation of optically-absorbing BC particles leads to a gradual increase in ATN from one 60-second period to the next. The aethalometer calculates black carbon concentrations by comparing the ATN value to the surface density loading of black carbon particles on the quartz filter.[155] The equation can be found in Figure A1 in Supplemental Material. The *microAeth AE51* is reported to have a measurement range of 0 – 1000 micrometers per cubic meter (µg/m^3) with a resolution of 0.001 µg/m^3 and precision of ± 0.1 µg/m^3. Microatholometers were cleaned and maintained according to manufacturer recommendations.[151]

A microcyclone (a type of size selective inlet) was used to collect particulate with an aerodynamic diameter of 1.6 µg or less ($PM_{1.6}$). Due to its formation via combustion, diesel particulate matter size distributions are predominantly in the ultrafine size range (0.1 µg in diameter or smaller).[139] In terms of particle count, the majority of the emitted diesel particulate matter are less than 50 nanometers in diameter, with mean particle diameters ranging from 60 – 120 nanometers (nm), which agglomerate and coagulate to comprise the largest category of particles by mass in the range of 50-1000 nm.[24,156] Ultrafine particles may agglomerate to a maximum diameter size of 1 µg. The microcyclone is used to prevent larger dust particles from the agricultural environment from overloading the filter and interfering with the microaethalometer's light transmission. This so called "shadow effect" happens when carbon-based particles layer on top of the black carbon loading on the filter and alter attenuation. Using the microcyclone thus reduced the risk of exposure misclassification, that is underestimating exposure concentrations due to instrument interference.

The flow rate on microaethalometers were calibrated with the microcyclones in line according to the Aethlabs Operating Manual.[151] Flow rates between 0 and 0.25 L/min were measured with a factory calibrated standalone *BIOS 510 Defender* DryCal Calibrator (Mesa Labs, Lakewood, Colorado) and adjusted manually on the microaethalometers via the computer software if flow rates measured by the standalone calibrator did not match the microaethalometer.

Out of a total of 51 BC samples, 5 (approximately 9.8%) were invalidated due to a blockage in the microcyclone resulting in a lower than desired flow rate (n=2), battery issues with the microaethalometers (n=2), and a spontaneous change in work tasks that resulted in a very short sample that did not involve diesel-powered equipment (n=1).

4.2.4 Analytical Methods

Passive NO_2 diffusion badges (28 personal samples and 2 field blanks) were analyzed by Assay Technology (Livermore, California, USA). The triethanolamine-treated filter converts nitrogen dioxide into stable nitrite ions, which were quantified by ion chromatography to assess the total mass of nitrogen dioxide that diffused onto the badge. Mass concentrations were calculated by dividing the reported level by the volume of air passively sampled.

Naphthalene (NAP), phenanthrene (PHE), and anthracene (ANT) samples (n=123) were extracted from XAD sorbent tube media (SKC) into dichloromethane in the Hammond

Laboratory at University of California, Berkeley in accordance with NIOSH Method 5515. Analyses to identify and quantify these compounds were performed by gas chromatography/mass spectrometry (GC/MS) (Agilent 7820/5977E) in the selected ion-monitoring mode with a 30m (5%-Phenyl)-methylpolysiloxane column (Agilent HP-5MS). Lab blanks were run for quality control. Serial dilution concentrations of standards (Fischer Scientific) were run with samples. PHE and ANT are isomers that co-eluted and are therefore reported as a summary. Sample results were blank-corrected by subtracting the average field blank and lab blank values from each of the sample values. The standard deviation for field blanks was 2.19 and 0.29 for NAP and PHE+ANT, respectively. Lab blanks standard deviations were 0.68 for NAP and 0.64 for PHE+ANT. Limits of detection (LOD) for PAHs compounds were determined by adding the average of the field and lab blanks to the standard deviation of the field and lab blanks multiplied by two. The LOD for NAP was 6.75 ng and the LOD for PHE+ANT was 3.33 ng; typically, this resulted in lowest detectable airborne concentrations of 30 ng/m^3 for NAP and 11 ng/m^3 for PHE+ANT.

Because BC measurement sensitivity is directly related to the loading rate of particles on a filter, sampling in environments where there are low BC concentrations and high flow rates can result in negative values and/or erroneously low or high values.[157,151] We used a sampling period ("timebase") of 60 seconds to reduce noise. During sampling periods of very low BC concentrations, the presence of instrument optical or electronic noise can lead to periods when the light attenuation (ATN) values remain unchanged or slightly decreased from one time period to the next.[155] The calculation of BC mass is based on successive differences in ATN; therefore noise may create an erroneously low value at one time point followed by a subsequent erroneously high value at the next. Various post-processing strategies can be employed to reduce noise in BC data from a moving average (simple, weighted, exponential) to advanced mathematical techniques.[158,159] However, these approaches do not take advantage of the additional information available in the ancillary ATN data provided by the aethalometer, which relates to the internal loading rate of the filter.[155] We used a validated and widely-used optimized noise reduction averaging (ONA) algorithm to reduce short-term fluctuations between readings that may generate negative concentration values in low-exposure conditions.[146,155]

A minimum change in ATN of 0.01 was used to maintain the original granularity of the data. Minimum change values greater than 0.01 could be used to smooth the data further; however, using the value of 0.01 ensures that data that is as close as possible to the data output from the monitor, but with significant excursions and noise omitted. The ONA uses variable time-averaging to determine the shortest time interval that meets the criterion for the minimum change in ATN, and then identifies if there were occurrences prior to that value that were also below that ATN value. If so, those ATN values are updated to the last occurrence in the sample spot time series and the BC values over that time window are averaged and applied within that time series window to replace the raw measurement values, which may be erroneous. Simply removing negative values from the data for analysis may positively bias the final black carbon values, therefore some negative values remain in the post-processed data for analysis, though there are fewer.[160] Consistent with other literature, we saw a decrease from 26% negative values in the raw BC data to 2% negative values in the post-processed data. A graph of raw BC data and post-processed BC data utilizing the ONA can be found in Figure 2 of the Supplementary Material.

We used field observations to define tasks associated with the BC time-series. When direct observations were not available to label some time periods, we estimated tasks based on our knowledge of workers' schedules, including 15-minute breaks in the mornings and afternoons and 30-minute lunch breaks and asked workers about their tasks at the end of the day.
Three personal samples were invalidated due to a blockage in the inlet of one of the microaethalometers, resulting in a low flow rate and underestimation of black carbon (n=2). Additionally, one personal sample was invalidated due to a battery issue in microaethalometer (n=1) not running for more than two minutes before turning off. No personal samples for NAP or PHE+ANT samples were invalidated; therefore, all 51 person-sampling days are presented here.

Fourteen background BC samples were collected among the 20 air monitoring days to assess baseline concentrations of BC on farms, as distinct from tractor-related emissions. Two samples were invalidated due to battery power issues on microaethalometers which resulted in short sampling periods. Four background samples were collected for NAP and PHE+ANT. All background monitors were placed on a tripod 4 feet in height away from the immediate work area where diesel-powered agricultural equipment was in use and between 200-500 yards away from paved roads. Background samples were placed near unpaved farm access roads on some occasions where gas-powered or diesel-powered vehicles drove by occasionally, which may represent background concentrations farmworkers would be exposed to from working on farms near unpaved farm access roads.

BC background samples from two sampling days were not saved correctly and are not available for comparison to the occupational samples collected on those days. One background sample for NAP and PHE+ANT was invalidated due to a loss of sorbent material during extraction in the lab.

PAH and BC data were lognormally distributed, demonstrated by right-skewed histograms and linear Q-Q plots for log-transformed data. Data were thus transformed prior to analysis in log linear regression models. Bivariate ($log(Y_i) = \beta_0 + \beta_1 X_1 + \varepsilon$) and multivariate ($log(Y_i) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \varepsilon$) log-linear regression models and Pearson's correlation tests were used to assess relationships. Values below the LOD were imputed by dividing the sample-specific LOD by the square root of 2, an appropriate method for lognormally distributed data. BC concentrations were right-skewed; therefore, analyses were conducted on log-transformed values. Model residuals were approximately normally distributed.

4.3 Results

4.3.1 Summary of Participant Information

We collected 50 personal air samples over 20 sampling days among 29 participants employed by four farms and one labor contractor in northern California from April - September, 2024 **(Table 1).** Fifty five percent of participants had repeated samples collected; four participants were sampled for four work shifts, three participants were sampled for three work shifts, nine participants were sampled for 2 work shifts, and 15 participants were sampled for one work shift.

Two participants were farm owners on small farms who performed the same type of work tasks as farmworkers. Twenty-eight percent of participants were female and 72% were male. Ninety percent of participants spoke Spanish as their primary language and were from Mexico, Guatemala, Honduras, and Peru. Participants' ages ranged from 21-75, with a median age of 37 and an average age of 40. The number of years that farmworkers had worked for that employer ranged from less than a year to 17 years, with a median of 1 year and average of 4 years. The two farm owners had been working on the farm for 40 and 53 years. Ninety three percent of participants (100% of those whose titles were farmworkers) identified as Latino/Hispanic, and the two farm owners identified as White and Asian.

Table 1. Participant Information

Demographic & Employment Characteristics		**Number of Participants**	**(Percent)**
Gender	Male	14	(70%)
	Female	6	(30%)
Race/Ethnicity	Latino/a	18	(90%)
	White	1	(5%)
	Asian	1	(5%)
Country of Origin	Mexico	10	(50%)
	Guatemala	2	(20%)
	Honduras	6	(30%)
	United States	2	(10%)
Age	21 - 30	6	(30%)
	31 - 40	6	(30%)
	41 - 50	3	(15%)
	51 - 75	5	(25%)
Years worked for current employer	0 - 5	12	(60%)
	6 - 11	4	(20%)
	12 - 17	2	(10%)
	50 - 55	2	(10%)
Primary Language	Spanish	18	(90%)
	English	2	(10%)
Job Title	Farmworker	17	(85%)
	Farmworker & Manager	1	(5%)
	Farmworker & Farm Owner	2	(10%)

Most participants' samples collected are among employees who worked near diesel exhaust for part or all of their work day. Two participants planned to work near diesel-powered equipment, but their tasks were changed by supervisors (one worked in a greenhouse away from exhaust and the other performed a weed-whacking task with gas-powered equipment). Tasks that participants conducted were representative of typical work they perform on a regular basis. We observed the following tasks performed by participants: turning compost; tree planting; driving tractors for mowing, spraying, weeding, tilling, planting, pruning, sledding, loading, and harvesting; and riding behind or walking behind tractors for planting, weeding, harvesting, and laying dripline. Riding behind the tractor involved sitting in one location on a platform or trailer attachment behind the tractor to perform tasks such as transplanting or weeding.

4.3.2 Air Sampling Results by Task and Farm

Table 2: Numbers of Samples and Participants by Farm

Farm	Number of Participants Sampled~	Number of Total Samples Collected
A	1	1
B	4	4
C	20	38
D	2	2
E	2	4
Total	29	50

~One employee's sample is not included in this summary table because of a spontaneous change in work tasks and very short sample duration

The primary tasks observed across all farms involved driving tractors. Based on the crop work being performed at four of the participating farms on 13 participant-sampling days, driving tractors was the only task sampled and observed at these locations. At Farm C, participants drove tractors as well as performed walking and riding tasks around tractors for a total of 37 participant-sample days. Participating workers at one farm performed a variety of tasks including walking or riding behind the tractor in addition to driving. Tasks samples are compared from this farm in **Figure 1**, and six different tractors were used for these tasks.

Table 3: Summary of NAP, PHE+ANT and BC Time-Weighted Average Concentrations by Farm*^

	NAP			PHE+ANT			BC**		
Farm	Arithmetic Mean (SD)	Geometric Mean (GSD)	Range (95th Percentile)	Arithmetic Mean (SD)	Geometric Mean (GSD)	Range (95th Percentile)	Arithmetic Mean (SD)	Geometric Mean (GSD)	Range (95th Percentile)
A	131 (NA)	NA	NA	32 (NA)	NA	NA	43,530 (50,407)	15,980 (7)	1 – 276,608 (163,798)
B	1,166 (1,373)	522 (4.6)	73 - 3,648 (3,111)	28 (5.8)	28 (1.2)	21 - 38 (36)	7,923 (24,721)	2,335 (7)	1 – 937,882 (22,743)
C	306 (1,350)	71 (3.0)	22 - 8,392 (357)	21 (18)	16 (2.2)	2.9 - 93 (49)	1,551 (6,989)	359 (6)	1 – 416,976 (5,765)
D	35 (19)	32 (1.8)	21 - 49 (48)	14 (1.0)	15 (1.1)	14 - 15 (15)	1,920 (4,063)	876 (3)	2 – 71,254 (6,582)
E	364 (287)	267 (2.6)	111 - 648 (637)	25 (19)	22 (1.9)	12 - 53 (48)	7,610 (25,661)	1,669 (8)	1 – 477,964 (34,581)
Total	398 (1,275)	98 (3.7)	21 - 8,392 (1,448)	22 (16)	17 (2.1)	2.9 - 93 (49)	2,910 (13,441)	503 (7)	1 – 937,882 (13,111)

* Minimum NAP and PHE+ANT values in range are the lowest detectable concentrations
^Time-Weighted Averages are presented based on the full-shift samples for NAP and PHE+ANT and were calculated from data points collected every minute over the shift for BC
**Negative values were converted to 1 only for the purpose of calculating geometric means and geometric standard deviations

Figure 1: Distributions of BC Concentrations by Task at One Farm

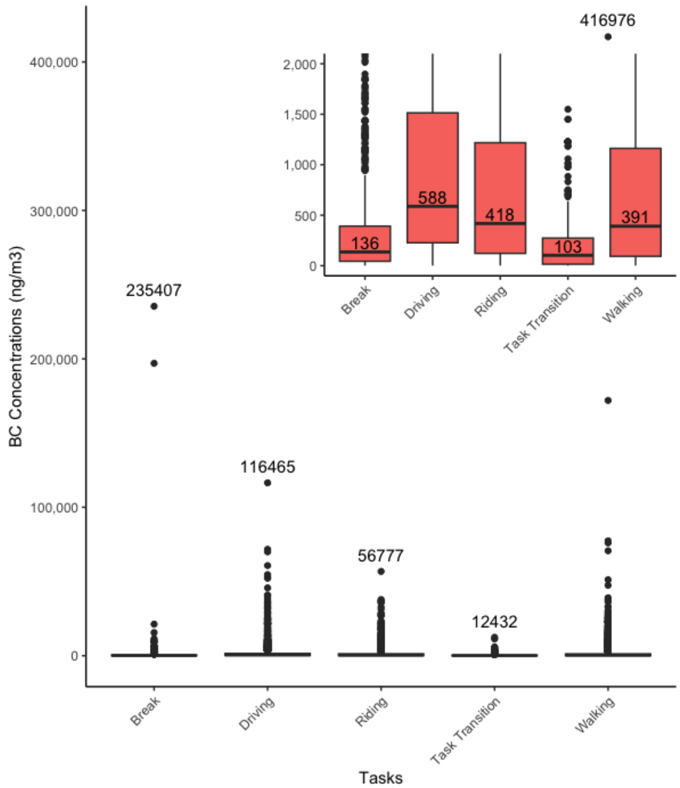

__Figure 8.__ Distributions of BC by task at Farm C are shown with maximum values labeled. Medians are labeled in the plot in the top right corner, which zooms in on values below the 75th percentile of the data. This plot represents 35 participant-sample days. Additional visualizations can be found in the Supplemental Material. The bottom of the box represents the 25th percentile (Q1) and the top of the box represents the 75th percentile (Q3), with the box representing the inter-quartile range (Q3-Q1); the center line shows the median.

Driving, filling tanks, and walking near the tractor resulted in statistically significant higher BC concentrations than other tasks observed across all farms **(Table 3).** Specifically, driving during the tasks of harvesting, loading, mowing, sledding, spraying, tilling, and turning compost were statistically associated with higher BC concentrations in a more detailed follow-up analysis **(Table 4)**. Loading tasks consisted of driving the tractor to transport harvested produce from one place to another, and did not include the use of the front loader attachment on the tractor. Spraying entailed driving through and spraying crop rows from liquid in a tank that was pulled behind the tractor. Sledding involved driving a tractor with a specific attachment to create sloped soil along crop rows. Walking during the task of harvesting resulted in statistically higher BC concentrations than other walking tasks (such as weeding, planting, and transplanting). Walking behind the tractor involved a worker following the slowly moving tractor to perform planting, weeding, or harvesting tasks; these tasks had the greatest variability in exposure concentrations due to the variable distances of the participant from the tractor throughout the day, as well as the highest maximum concentration measured at this farm.

Table 4: Black Carbon Concentrations Summarized by Task Categories (ng/m^3)

Task	**Number of Participants Sampled^**	**Number of Minutes Sampled**	**Arithmetic Mean (SD)**	**Geometric Mean (GSD)**	**95th Percentile (Max)**
Walking	16	3,789	1,824 (9,605)	335 (7)	6,692 (416,976)
Riding	10	1,774	1655 (4,072)	427 (5)	6,941 (56,777)
Driving, total	13	7,231	4,744 (17,973)	1,077 (6)	18,351 (937,882)
Filling Tank	2	7	20,569 (21,048)	15,773 (2)	52,151 (67,952)
Greenhouse*	1	222	17 (290)	13 (4)	423 (1,617)
Weed-whacking*	1	436	874 (1,634)	344 (4)	3,551 (16,278)

*Not using diesel-powered equipment
^Some participants sampled for more than one day

Table 5: Black Carbon Concentrations Stratified by Specific Driving Tasks (ng/m³)*

Task	Number of Participants Sampled^	Number of Minutes Sampled	Arithmetic Mean (SD)	Geometric Mean (GSD)	95th Percentile (Max)
Harvesting	2	328	3,099 (7,094)	945 (4.4)	14,332 (69,960)
Loading	1	14	1,687 (1,994)	838 (3.4)	5,579 (6,085)
Mowing	5	1,718	9,303 (23,149)	2,408 (6)	35,872 (477,964)
Sledding	1	150	8,920 (26,293)	2,286 (5)	32,347 (240,107)
Spraying	2	489	13,355 (43,285)	4,588 (6)	31,092 (937,882)
Tilling	4	1,519	2,119 (5,301)	940 (3)	6,600 (116,465)
Turning Compost	1	469	2,943 (3,099)	1,503 (4)	9,679 (18,430)

*These driving tasks resulted were statistically associated with higher BC concentrations than other tasks.
^Some participants sampled for more than one day

The task we designated as a comparison, working in the greenhouse, did not involve working near diesel-powered equipment and resulted in substantially lower concentrations than the other tasks**.** The peak concentrations during greenhouse work were likely due to a diesel-powered truck driving by infrequently for hauling produce. Similarly, some breaks resulted in high concentrations when participants were in the vicinity of diesel-powered tractors or trucks. BC concentrations measured during breaks had an arithmetic mean of 749 ng/m^3, a 95th percentile of 1,832 ng/m^3 and a maximum of 235,407 ng/m^3.

Participants who drove tractors also had higher NAP concentrations compared to those who performed other tasks **(Figure 2)**; however, these differences were not statistically significant. PHE and ANT concentrations were highest on average among participants who walked near the tractor, followed by driving the tractor, and these differences in concentrations were not statistically significant. Tractor drivers have significantly higher exposures of NAP and BC compared to workers in other task categories**.** Due to the integrated nature of PAH samples, we were not able to analyze PAH samples by short task periods; rather, we estimated daily time-weighted average concentrations associated with tasks that were performed for 75% of the day or more.

Figure 2: Participant Concentrations of (A) NAP and (B) PHE+ANT by Task

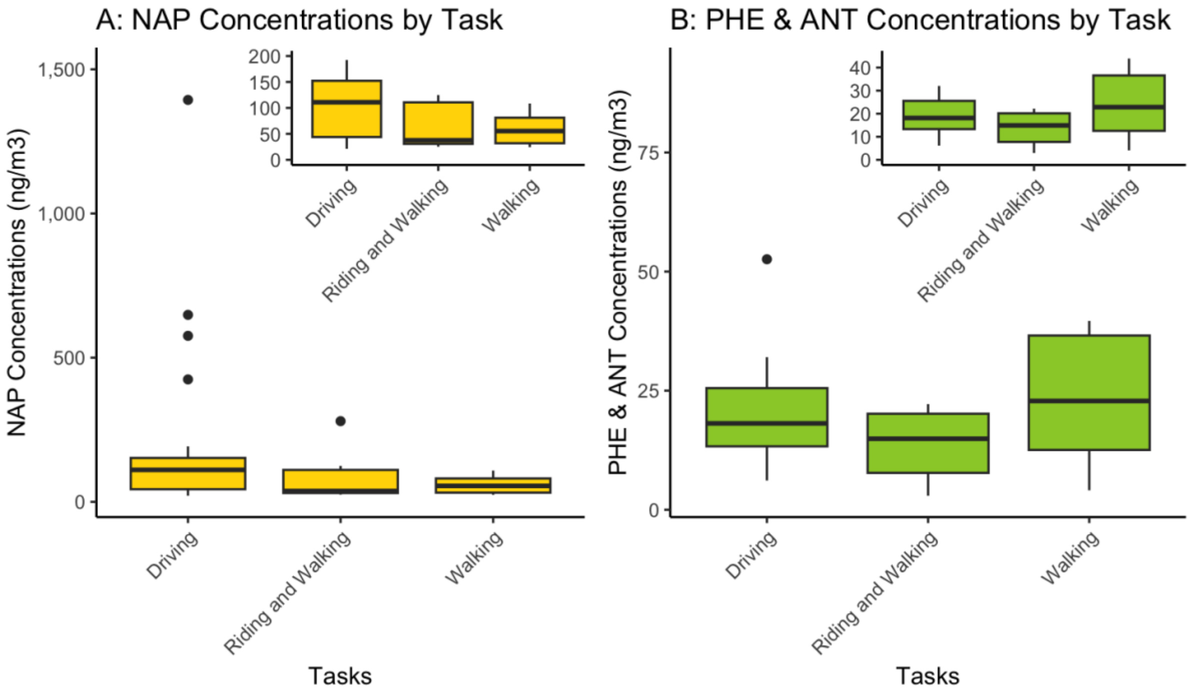

Figure 2. *All data is displayed in the larger plot. The inset plot in the top right corner displays distributions of NAP and PHE+ANT have been plotted on a truncated y-axis to aid in the visual comparison of concentrations measured across tasks. The maximum value on the y-axis for each graph was chosen so that the 75th percentile of the distribution was within the plot. Although PAH samples were integrated, we categorized tasks based on what participants were doing for 75% of more of their workday. These plots have excluded three personal samples for which participants were performing a variety of tasks or were not around diesel-powered equipment, thus this plot includes 47 participant-sample days. A. Naphthalene. B. Phenanthrene and Anthracene. Note the different scales on the y-axes. The bottom of the box represents the 25th percentile (Q1) and the top of the box represents the 75th percentile (Q3), with the box representing the inter-quartile range (Q3-Q1); the center line shows the median.*

Figure 3 illustrates the real time BC concentrations collected every minute among three participants working together to transplant “starts” (young plants started in the green house). Each participant wore their own microaethalometer. The tractor pulled a transplanter attachment that digs a small hole in the soil and drops a start into the hole at the desired interval as the tractor moved forward. A worker sits in a chair on the transplanter platform to insert the starts into the machine. The tractor was stopped periodically to refill starts onto the transplanter platform. Sometimes the tractor engine was turned off during a task transition (such as refilling starts or communicating about which starts to plant in which rows), and other times the engine was left on (“idling”).

Using microaethalometers to measure BC every minute allowed for more detailed analysis of exposure concentrations and farm work tasks than with the integrated samples of NAP, PHE+ANT and nitrogen dioxide. A table of daily BC summary statistics by work shift for each sampling day can be found in the Supplementary Material.

Figure 3: Time Series of BC Concentrations Among Three Participants

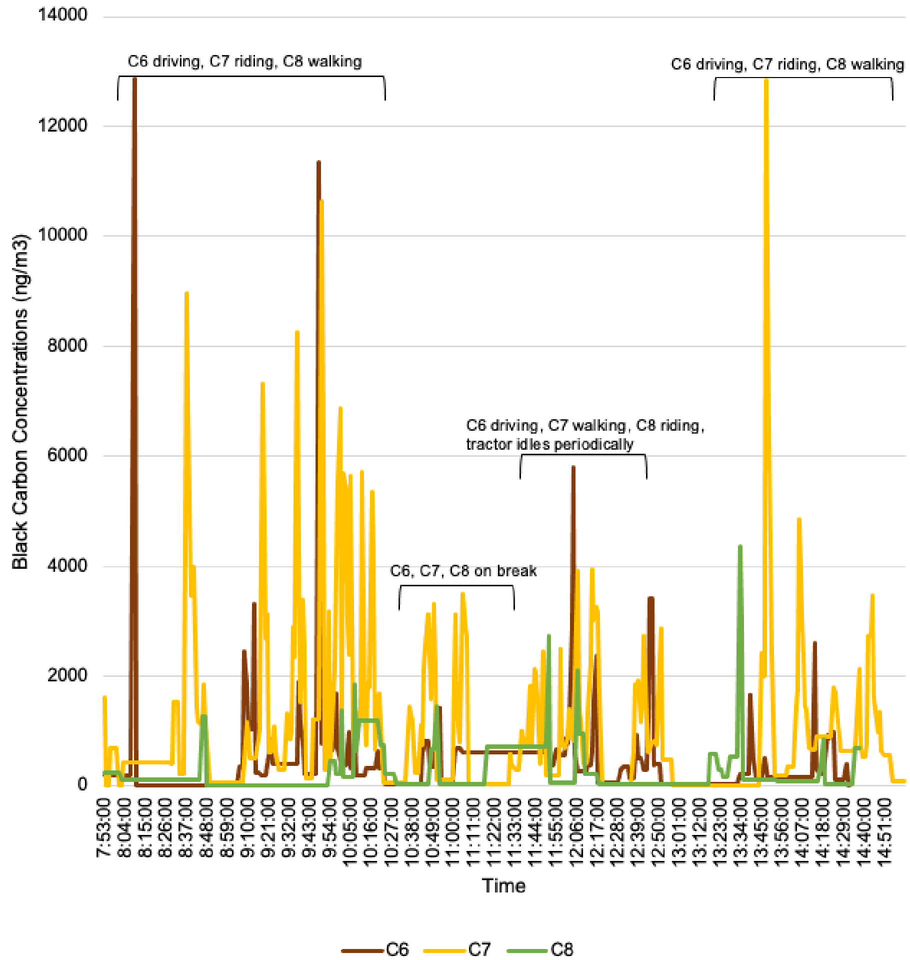

Figure 3. *One-minute averages were collected on microaethalometers worn by three participants (C6, C7, and C8) working together to transplant. These one-minute concentrations are displayed here over the sampling period.*

Participant C7 had consistently higher exposures than the other two workers while riding on the transplanter platform. Like C7 and C8, participants typically rotated job tasks between riding and walking, for tasks like weeding, planting, transplanting, and harvesting, however driving is a specialized role in which less job rotation was observed. Some other participants performing walking tasks for weeding, planting, watering, or harvesting on other days had higher exposures compared to C8's concentrations, due to the variability in proximity to the tractor and each individual tractor's diesel exhaust emissions rate.

This type of qualitative analysis of microaethalometer data was conducted in addition to other quantitative analyses for all sampling days to understand which tasks and tractor activities were associated with reduced or elevated exposures. Elevated exposures across the sampling days were associated with accelerating and reversing. Acceleration can occur backwards or forwards in the process of speeding up from a stopped position, and it represents a known cause of elevated vehicle emissions.[161] Reversing may be associated with an increased risk of exposure because the tractor may turn into its exhaust plume. It was also observed that idling commonly took place across farms when there was a pause in the work task. High exposure concentrations were observed while tractors were idling, specifically when employees loaded starts onto the transplanter platform, adjusted tractor mowing and weeding attachments, and filled a tank while standing near the tractor tailpipe exhaust.

Figure 4: BC Concentrations Among Drivers Across all Farms

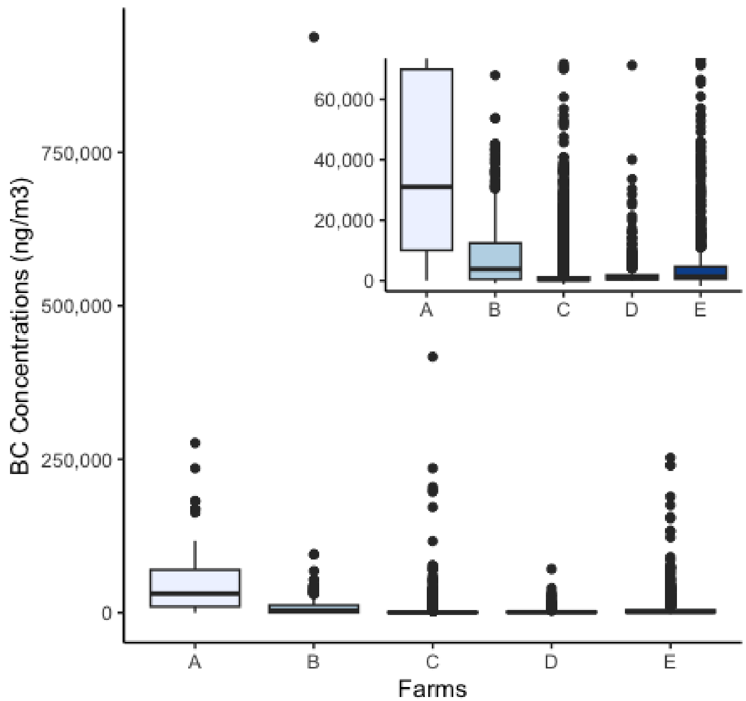

Figure 4. *BC distributions are shown by farm. The plot in the top right corner zooms in on values below the 75^th^ percentile of the data. The bottom of the box represents the 25^th^ percentile (Q1) and the top of the box represents the 75^th^ percentile (Q3), with the box representing the inter-quartile range (Q3-Q1); the center line shows the median.*

BC concentrations among tractor drivers across all farms varied **(Figure 4)** indicating the potential impact of tractor characteristics on exposure. The magnitude of exposures to tractor drivers is a function of the tractor itself as well as the duration of exposure. Most participants who drove tractors during their shift spent approximately 90% of their work time driving. Additionally, there are many tractor characteristics that affect diesel exhaust concentrations such as tailpipe location and design, cab style, potential use of fuel additives, and the Tier of the tractor, which indicates age, fuel efficiency, and engine characteristics designed to reduce emissions.

BC and NAP were moderately significantly, positively correlated (p-value < 0.05) and BC and PHE+ANT were moderately significantly, positively correlated (p-value < 0.05) **(Figure 5).** NAP and PHE+ANT were not significantly correlated**,** and there may be engine differences by tractor driving these differences.

Figure 5: Scatterplot of Logtransformed NAP, PHE+ANT and BC Relationships by Farm

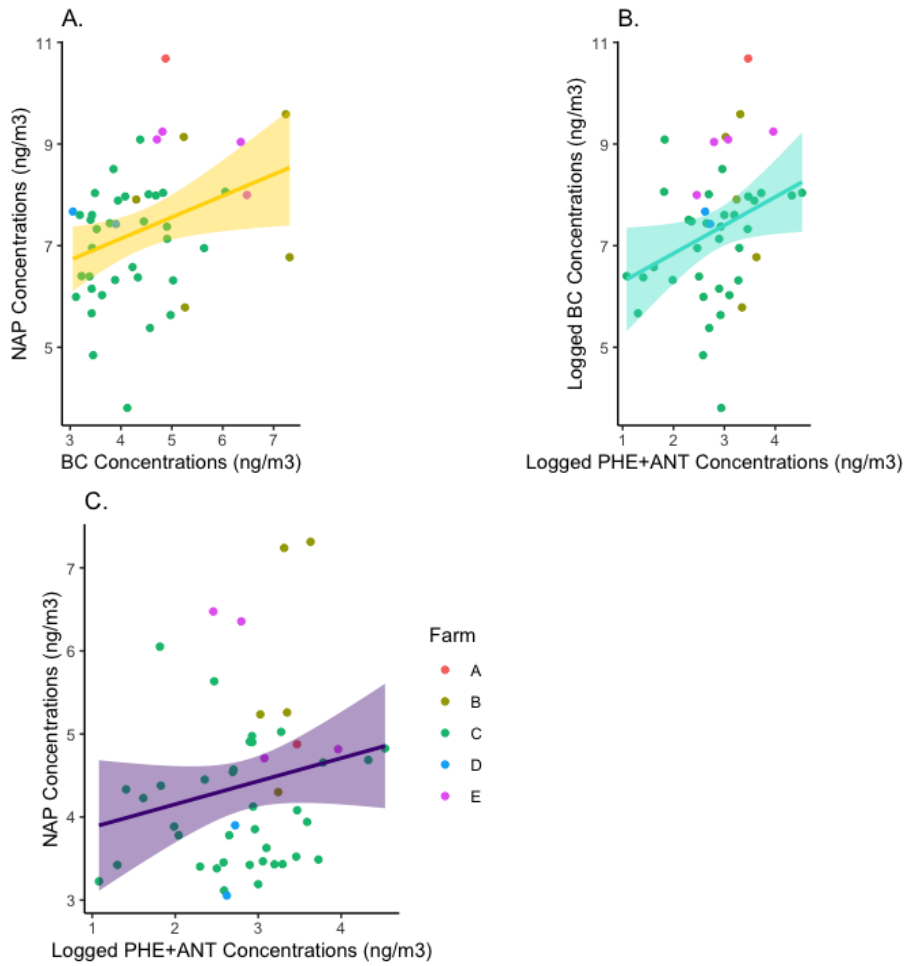

Figure 5. *Scatterplots of NAP, PHE+ANT and BC concentrations by farm and bivariate regression line representing the log linear relationship ((*$log(Y_i) = \beta_0 + \beta_1 X_1 + \varepsilon$*) A. Relationship between logtransformed BC and NAP concentrations (*$R^2 = 0.33$*). B. Relationship between logtransformed BC and PHE+ANT concentrations (*$R^2 = 0.30$*). C. Relationship between logtransformed NAP and PHE+ANT concentrations (*$R^2 = 0.20$*). Plots maintain a 1:1 aspect ratio.*

4.3.3 Air Sampling Results by Tractor

There were fourteen different tractors manufactured by four different companies observed in the study on sampling days. Tractor Tier categories were recorded based on farmer knowledge of the purchase date of the tractor or estimated based on the model number and appearance of the tractor. The two oldest tractors in the study were approximately 30 years old (Tier 0 or Tier 1) and workers driving them had some of the highest time-weighted average exposure concentrations in the population of participants **(Figure 6)** (43,530 ng/m^3 and 10,346 ng/m^3, respectively). A tractor driver at farm B (Tier 2 or Tier 3) also had elevated concentrations, possibly due to the nature of this driving task in moving back and forth turning and loading compost (14,571 ng/m^3). The three newest tractors in the study (Tier 4) were approximately 5 years old or less and two drivers of these tractors had lower exposure concentrations compared to others. Only one tractor in the study at farm B used Diesel Engine Fluid (DEF), which is designed to reduce the production of diesel exhaust air pollutants; we found that the driver of this tractor, which was also a Tier 4 tractor, had lower BC concentrations than tractor drivers of other Tier 4 tractors.

Figure 6: Distributions of BC Concentrations by Tractor

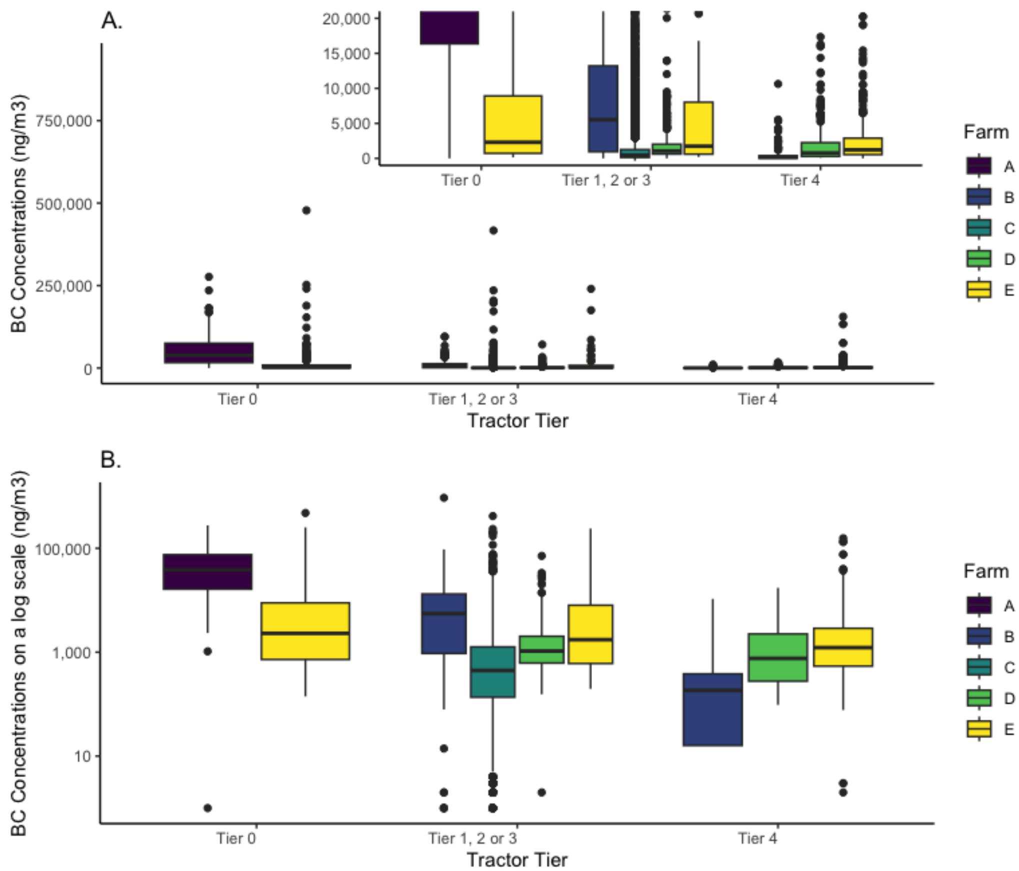

Figure 6. *A. Measured BC concentrations with top right corner plot highlighting the comparisons of concentrations below 20,000 ng/m3. B. BC concentrations plotted on a logtransformed y-axis. One tractor has been excluded from this Figure because it was used for a very short period (10 min) and was therefore not comparable to other tractors. The bottom of the box represents the 25th percentile (Q1) and the top of the box represents the 75th percentile (Q3), with the box representing the inter-quartile range (Q3-Q1); the center line shows the median.*

Among the 28 samples collected for nitrogen dioxide, 89% were not detectable. The three samples that were detected above the LOD (0.02 ppm) were at levels of 0.03, 0.04, and 0.10 ppm. The arithmetic mean was 0.06 ppm and standard deviation was 0.04 ppm. These samples were collected when participants were driving older tractors for the tasks of mowing (Tier 0), front loading (Tier 0), spraying and turning compost (Tier 1, 2 or 3). These tractors were generally older than others in the study population.

Many farms had tractors in a similar age range; however, Farm E had both very new and very old tractors **(Figure 7).** The older Tier 0 tractor had a higher median and higher maximum BC concentrations than the two newer Tier 4 tractors used. The Tier 0 tractor was used for a specific task to pull a heavy tractor attachment for mowing tall weeds, reportedly the most powerful tractor to perform that task. All tractors performed a similar amount of turning around at the end of crop row and driving forward without substantial reversing of the tractor.

Figure 7: BC Concentrations Measured Among Drivers Using Tier 0 and Tier 4 Tractors at Farm E

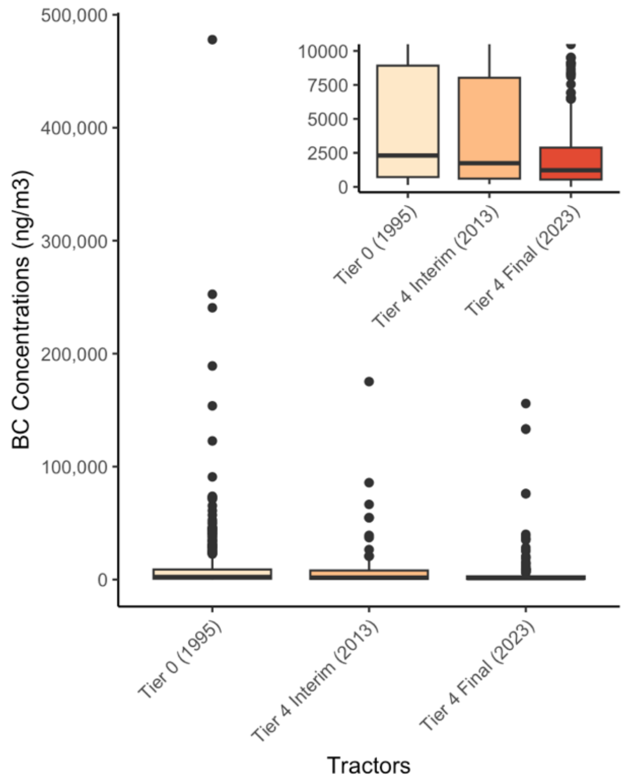

Figure 7. *BC concentrations measured among drivers using Tier 0 and Tier 4 tractors at Farm E. The inset plot in the top right corner zooms in on values below the 75th percentile of the data. The bottom of the box represents the 25th percentile (Q1) and the top of the box represents the 75th percentile (Q3), with the box representing the inter-quartile range (Q3-Q1); the center line shows the median.*

Participants who drove tractors with low tailpipes and closed cabs had higher mean full-shift exposures to BC (7,923 ng/m^3), NAP (1,166 ng/m^3), and PHE+ANT (28 ng/m^3) than drivers of other tractors **(Figure 8).** Workers driving tractors with high tailpipes and open cabs had the lowest mean exposures for all three of these diesel constituents (4,267 ng/m^3 BC, 263 ng/m^3 NAP, and 22 ng/m^3 PHE+ANT). These differences were statistically significant and tailpipe location and cab style explained 12% of the BC data. Personal samples among drivers of tractors with open cabs and high tailpipes had the lowest NAP concentrations, and they were statistically significantly lower than tractors with low tailpipes and closed cabs. Tailpipe location and cab style were significant predictors of NAP, explaining 20% of the variation in NAP concentrations.

Tailpipe location and cab style predicted PHE+ANT concentrations, though the association was not statistically significant.

Figure 8: Concentrations of BC, NAP, and PHE+ANT by Tailpipe Location and Cab Style

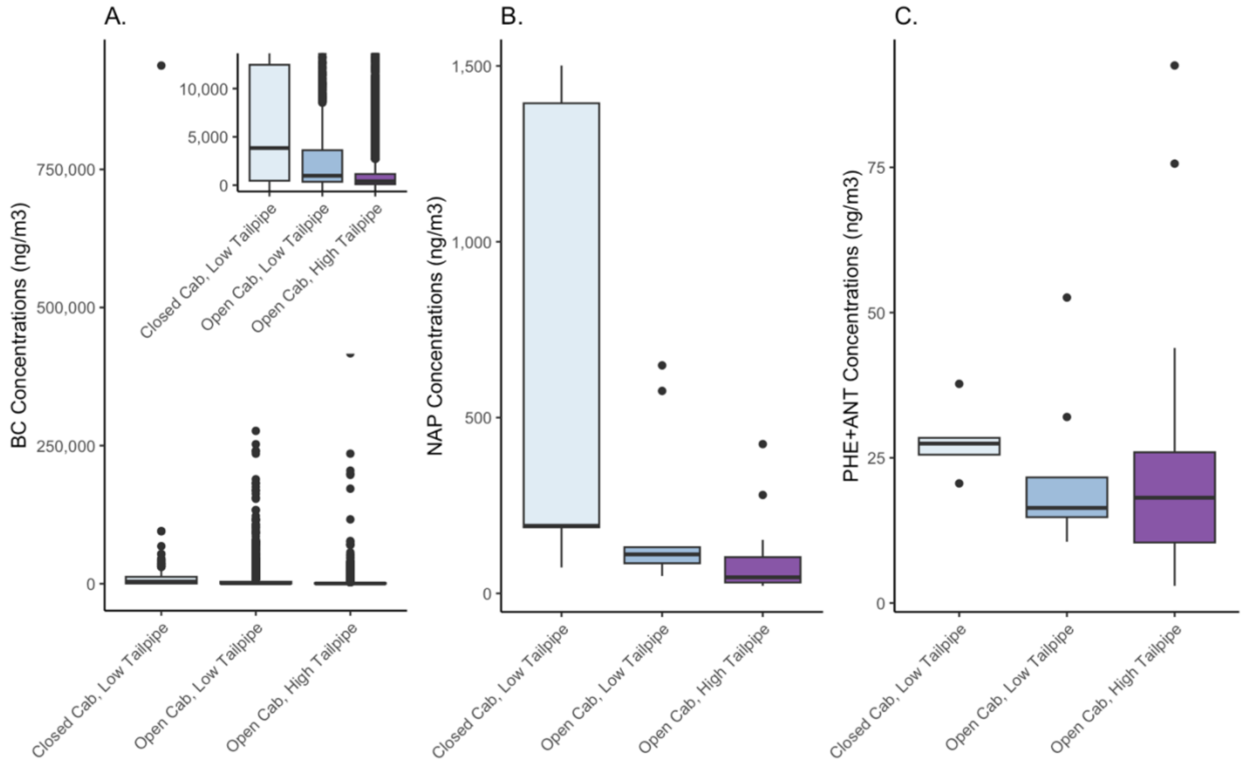

Figure 8. *A. Black Carbon. B. Naphthalene. C. Phenanthrene and Anthracene. Note different scales on y-axes. Distributions of BC in plot A are shown on a truncated y-axis in the top right corner to display the 75th percentile of the data to aid in visual comparison. The y-axes of plots B and C are not truncated or transformed. The bottom of the box represents the 25th percentile (Q1) and the top of the box represents the 75th percentile (Q3), with the box representing the inter-quartile range (Q3-Q1); the center line shows the median.*

4.3.4 Summary of Background Samples Collected

Background monitors were placed on a tripod 4 feet in height away from the immediate work area where diesel-powered agricultural equipment was in use and between 200-500 yards away from paved roads. Background samples were placed near unpaved farm access roads; on some occasions gas-powered or diesel-powered vehicles drove by occasionally, which may represent background concentrations farmworkers would be exposed to from working on farms. Time-weighted average background BC concentrations ranged from 15 – 383, with a mean background concentration of 166 ng/m^3 and a maximum minute-long excursion of 5,083 ng/m^3 **(Table 5 and Figure 9).** The background mean and maximum time-weighted average concentrations are one to two orders of magnitude lower than those of the personal samples for BC samples. Time-weighted average background concentrations for NAP ranged from 7 – 36 ng/m^{3}and for PHE+ANT ranged from 1 – 30 ng/m^3 **(Table 6)**; mean and maximum concentrations of background samples are one to two orders of magnitude lower than personal samples for NAP, with a smaller magnitude of difference for PHE+ANT samples, but still with a clear distinction between background and personal samples.

Table 6: Summary Background and Personal BC Time-Weighted Average (TWA) Samples (ng/m^3)

	Number of Sampling Days	Arithmetic Mean of TWAs	Range of TWAs	Standard Deviation of TWAs	Geometric Mean of TWAs	% of data collected every minute that exceeds 2000
Background Samples	12	166	15 - 383	114	63	0.15%
Personal Samples	20	3,564	114 – 43,530	6,813	1,525	22%

Table 7: Summary Background and Personal NAP and PHE+ANT Time-Weighted Average (TWA) Samples (ng/m^3)

		NAP				PHE + ANT			
	Number of Sampling Days	Arithmetic Mean of TWAs	Range of TWAs	Standard Deviation of TWAs	Geometric Mean of TWAs	Arithmetic Mean of TWAs	Range of TWAs	Standard Deviation of TWAs	Geometric Mean of TWAs
Background Samples	3	22	7 - 36	15	18	12	1 - 30	15	6
Personal Samples	20	398	21 – 8,392	1,275	98	22	2.9 - 93	16	17

Figure 9: Background Concentrations of Black Carbon Across 12 days

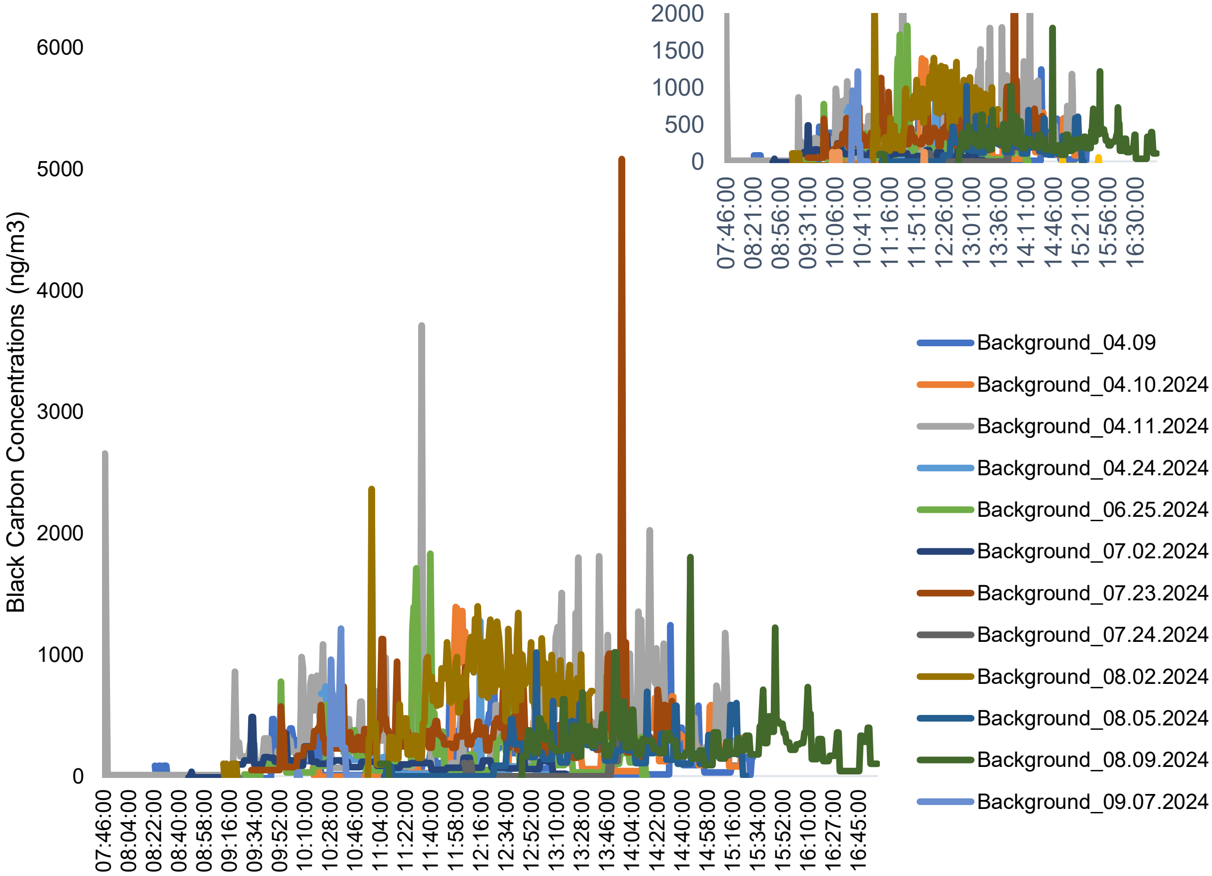

Figure 9. *Time series concentration data across one-minute averages for background samples. Background samples were placed on a tri-pod 4 feet in height on the farms away from the immediate work area where diesel-powered agricultural equipment was in use and between 200-500 yards away from paved roads. Background samples were placed near unpaved farm access roads on some occasions where gas-powered or diesel-powered vehicles drove by occasionally, which may represent the background concentrations that farmworkers would be exposed to from working on farms near unpaved farm access roads.*

4.4 Discussion

This study presents previously uncharacterized information about diesel exhaust exposure among farmworker populations. California contains one of the largest agricultural economies in the world, and both large and small farms utilize diesel-powered equipment. The San Joaquin Valley, in particular, which is one of only two areas in the nation experiencing extreme ozone nonattainment, contains over 50 percent of California's agricultural equipment.[7] Ozone is a criteria air pollutant that is formed in the presence of sunlight from constituents of diesel exhaust. Other criteria air pollutants emitted in diesel exhaust include nitrogen dioxide and particulate matter. In addition to characterizing exposures to farmworkers, this study offers insights into the regional impact of diesel-related air pollution in agricultural communities.

4.4.1 Black Carbon

We investigated personal black carbon (BC) exposure using the same brand and model (AethLabs AE51) of microaethalometers that were used in previous research to characterize BC as a marker of diesel exhaust among farmers. Stapleton et al. collected personal samples among 16 farmers over 20 days during the 2015 harvest season in Iowa.[150] Sauvé et al. expanded that study to include an additional 15 farmers for a total of 63 sampling days.[146] We compared our results to those found by Stapleton et al. and Sauvé et al. **(Table 7).**

Stapleton et al. found a median daily geometric mean of 330 ng/m^3, which is lower than what we observed. We calculated their median daily arithmetic mean from the data they reported in Table 1 of their Supplementary Material; this value of 1200 ng/m^3 was similarly lower than our findings (1735 ng/m^3). Expanding upon Stapleton et al.'s sampling population to include 63 samples, Sauvé et al. found a daily Minimum Variance Unbiased Estimator Arithmetic Mean (MVUE-AM) of 2,110 ng/m^3 and a geometric mean of 340 ng/m^3. Similarly, these values are lower than our measured values of 2,911 ng/m^3 and 503 ng/m^3, respectively. Some tasks performed by farmers in Iowa are not comparable to the tasks performed on participating northern California farms, such as grain bin work (which included loading) and animal work; these tasks were not included in our comparisons**.** Loading was a task that was also different between our study and that of Sauvé et al. because of the different nature of the tasks (and different associated crops) between the farms in Iowa and the two farms where loading was performed in our study.

Both prior studies documented that farmers have many tasks during their work day; however, the farmworkers in our pilot study performed only 1-2 tasks per work day. Farmers may have more diversity in their tasks, more autonomy in the tasks they perform, and thus have the ability to cycle through high and low exposure tasks throughout the day. This contrasts with the experience of farmworkers, who tend to have less autonomy in the tasks they perform, and who may have higher diesel exhaust exposures than farmers if they work one high exposure task for a significant portion of their work day. Stapleton et al. documented that only 39% of farmer's tasks involved a diesel-powered vehicle, which partially explains why the concentrations are lower than those we measured. More information is needed to fully characterize BC and diesel exhaust exposures during agricultural tasks; however, these findings suggest that farmworkers working near tractors may face a higher exposure than farmers.

Table 8. Comparison of Black Carbon Concentrations Measured Among Farmers and Farmworkers in Three Investigations (ng/m³)

Task	Year	Population	Number of sampling days	Arithmetic Mean* (SD)	Geometric Mean (GSD)	95th Percentile (Max)	Author
Driving, total	2015	Farmers	20	5800 (NR)	600 (6,900)	NR (288,400)	Stapleton et al.
	2015-2016	Farmers	63	2,110 (NR)	330 (6,900)	9,720 (NR)	Sauvé et al.
	2024	Farmworkers	46	4,744 (17,973)	1,077 (5.5)	18,351 (937,882)	Present study
Driving, harvesting	2015-2016	Farmers	63	1,180 (NR)	270 (5,600)	4,320 (NR)	Sauvé et al.
	2024	Farmworkers	46	3,099 (7,094)	945 (4.4)	14,332 (69,960)	Present study
Driving, Soil prep & planting	2015-2016	Farmers	63	3,070 (NR)	490 (6,800)	16,350 (NR)	Sauvé et al.
	2024	Farmworkers	46	2,119 (5,300)	940 (3.4))	6,601 (116,465)	Present study
Driving, loading	2015-2016	Farmers	63	4,040 (NR)	740 (6,300)	18,550 (NR)	Sauvé et al.
	2024	Farmworkers	46	1,687 (1,994)	838 (3.4)	5,579 (6,085)	Present study

NR = Not Reported
*Minimum Variance Unbiased Estimator-Arithmetic Mean reported by Sauvé et al.

Tractors have many different characteristics that may affect diesel exhaust exposure concentrations for nearby agricultural workers, including the style of the cab, the location of the tailpipe, the Tier category of the tractor, and specific engine characteristics. Tier categories were established by the U.S. EPA beginning in the mid-1990's to reduce off-road diesel equipment emissions via improved engine technologies. Since then, Tiers 1 - 4 have been implemented in a phased regulatory approach for engine manufacturing. Engines manufactured between 2011-2014 were subject to Tier 4 "Interim" emission standards and engines manufactured after 2014 were subject to Tier 4 "Final" emissions standards, which at the time of this publication is the highest Tier mandated by the U.S. EPA.[162] The State of California has started to work on potential amendments to further update these emission standards to Tier 5.[163]

Our findings are consistent with the limited results presented from Stapleton et al. and Sauvé et al. and other literature reporting that older tractors resulted in greater exposure concentrations for workers. In our direct comparison of three tractors at one farm, the driver of the Tier 4 Interim tractor had higher personal concentrations than the driver of the Tier 4 Final tractor, which may in part be due to the Tier engine technology upgrades that were required with the Tier 4 Final regulation. Additionally, the Tier 4 Interim tractor was used in a small vineyard next to a paved city road where it may have been influenced by cars, trucks and heavy-duty agricultural equipment driving by periodically, though the contribution of BC from this source is likely small as illustrated by the background samples we collected.

Although the differences are not statistically significant, we observed differences in exposures based on tractor Tiers, which indicate age of the engine and emission reduction technology implemented in the engine. The best way to reduce exposure for farmers and farmworkers is to use electric or Tier 4 tractors, which are designed for fuel-efficiency and reduced air pollution emissions. However, modifying tailpipes to be in a high position and pointing away from the driver are also methods to reduce exposure based on our findings.

We observed that drivers of tractors with high tailpipes and open cabs resulted in the lowest exposures to BC. This was likely due to the direction of the tailpipe opening, and the increased ventilation that open cab tractors provide. The previously described investigations by Stapleton et al. and Sauvé et al. found higher black carbon exposures among tractor drivers of open cabs, which contrasts with our findings. They did not report the location of the tailpipe or the direction it was facing. Many tractors are designed to have high tailpipes with an opening that faces backwards towards the driver. All but one of the tractors with high tailpipes in front of the driver in our study had been modified to move the opening of the exhaust facing away from the driver instead of towards the driver. This may have led to lower exposure for drivers of open cab tractors in our study compared to the findings of Sauvé et al. Additionally, Sauvé et al. collected data in Iowa, where atmospheric temperature and humidity are different from California, particularly during the harvest season. Afternoon wind was consistently observed in the afternoons at one farm (Farm C) in our study, which would reduce exposures due to ventilation and dilution of diesel exhaust pollutants.

Our findings that drivers had higher diesel exhaust exposures on average than workers performing other tasks is consistent with the work of Stapleton et al. and Sauvé et al. We found that exposures during the task of driving are higher regardless of specific tractor, but the highest peak exposure concentrations occurred during acceleration and reversing activities (i.e. front loading, turning tractor around at the end of a crop row). Individual tractors also introduce variability in the exposure among drivers. The magnitude of exposure to tractor drivers is a function of the tractor characteristics itself as well as the full-shift length duration of exposure. Because tractor drivers are a specialized job category, driving resulted in a longer duration of exposure than other tasks.

Walking near the tractor to manually harvest produce resulted in statistically higher BC concentrations than other walking tasks. This is likely because workers pick crops as the tractor moved away from them and then walk close the tractor to drop off the picked produce onto the attached platform. With the other walking tasks of planting, transplanting, weeding, and laying dripline, workers were mostly behind the tractor at a greater distance. It is recommended that tasks be performed with tractor engines turned off instead of idling whenever possible to reduce exposures, particularly when the task involves working near the tractor tailpipe exhaust.

Background samples we collected on the farms show that the background levels of BC in the air due to vehicle traffic on the farm or on nearby roads do not substantially contribute to the concentrations of personal samples or the exposures that workers experience associated with working near diesel-powered tractors. Our arithmetic and geometric mean background concentration of BC (168 ng/m^3 and 123 ng/m^3, respectively) are lower than urban ambient concentrations measured in the center of Fresno, CA, a small city in the San Joaquin Valley, from 2019 and 2022.[164] Measurements ranged from 31 – 4,886 ng/m^3 with arithmetic mean of 619 ng/m^3 and geometric mean of 414 ng/m^3. Our background concentrations are also lower than the suburban background concentrations measured outside of four northwestern European cities from 2013 to 2015 (200 ng/m^3).[165]

There have been many studies of diesel exhaust exposure in occupational settings, with black carbon or elemental carbon commonly measured as surrogate compounds, though the agricultural sector has not been well characterized.[146] Elevated DNA adducts, which are an indicator of carcinogenicity, have been associated with occupational exposure. In the 30 human epidemiological studies reviewed by the California Office of Environmental Health Hazard Assessment (OEHHA) in their Scientific Review Panel Report from 1998, long-term occupational exposure to diesel exhaust was associated with a 40 % increase in the relative risk of lung cancer. They have not identified a threshold of exposure under which lung cancer would not be anticipated; however, a Reference Exposure Level (REL) of 5,000 ng/m^3 (5 ug/m^3) was established by OEHHA as a threshold of exposure to diesel exhaust particulate matter below which non-cancer effects are not expected.[166] This REL was established in 1998 and took into account toxicological data from animal experiments, without considering data collected among humans. There is evidence of associations between diesel exhaust exposure and adverse non-cancer effects to the immune, respiratory and cardiovascular systems that warrants an update to this REL. This REL takes into account the general public, including populations that may be more sensitive to the effects of diesel exhaust exposure. Chronic inhalation exposure to this level over a lifetime may increase the risk of adverse respiratory health outcomes.[166] Although this guidance level was not necessarily designed for comparison to occupational groups, we use it as a comparison here because of the concern for risks of non-cancer health effects that farmworkers may face. Five participants over seven sampling days had work shift arithmetic mean BC concentrations (as time-weighted averages) that exceed this REL. Five of them were driving tractors during their shift and one of them was walking behind a tractor and manually harvesting produce. As described in the introduction, particulate matter is composed of 30-70% black carbon, therefore we estimate that 17 participants had time-weighted average arithmetic mean exposures greater than 2,500 ng/m^3 diesel exhaust particulate matter, or 50% of the REL.

An investigation of BC concentrations was performed across 60 work shifts of railroad workers at three large enclosed railway stations in European cities. Full-shift mean exposures ranged from 600 – 20,800 ng/m^3 and 1-minute peak exposures reached 773,000 ng/m^3.[167] These results are in the same range as BC concentrations measured among tractor drivers in our results. Average and median concentrations we measured are lower than average and median concentrations measured among three studies of professional drivers of diesel taxis in Spain and England; however, maximum concentrations we measured (in the 99th percentile) were higher than those measured in these studies, indicating that farmworkers may have lower average daily exposures compared to taxi drivers, but higher spontaneous exposures to very high concentrations of BC, which may present acute respiratory or cardiovascular health concerns.[168–170] Farmworkers in this study who worked near or with diesel-powered equipment, regardless of task performed, experienced exposures to black carbon higher than ambient levels found in the general environment, indicating that farmworkers are more highly exposed than the general public. The exception was one farmworker who worked in a greenhouse and was not around diesel-powered equipment, which effectively served as an exposure control.

As discussed in the introduction section, EC and BC both measure the non-organic carbon content of particulate matter, but are measured via two different methods. Studies show that EC and BC are often well-correlated, but the degree to which they are correlated can vary by particle composition, particle aging in the atmosphere, as well as other factors such as season.[171] Calibration factors can be used to convert BC to EC or vice versa when both measurements are concurrently co-located. All available exposure guidelines have been developed for EC rather than BC, which limits our ability to directly compare our results to the exposure guidelines below.

The European Union (EU) has established an occupational exposure limit to diesel exhaust of 50,000 ng/m^3 (50 ug/m^3) based on cancer risk above that threshold with chronic occupational exposure. The EU standard is based on a measurement of diesel particulate matter as submicron elemental carbon. A recommended TLV for diesel particulate matter expressed as elemental carbon was previously proposed as 20,000 ng/m^3 but not formalized.[172–174] Mining Safety and Health Administration (MSHA) has established a permissible exposure level (PEL) for diesel exhaust based on total carbon of 160,000 ng/m^3 among miners only, a highly exposed population with high rates of lung cancer.[175] TLVs are health-based guidelines, whereas Permissible Exposure Limits (PEL) set by the federal or state Occupational Safety and Health Administration (OSHA) are regulatory compliance levels mostly based on the 1968 TLVs. Additional guidance levels in the US are warranted.

Only one study to our knowledge investigated EC in off-road diesel exhaust among agricultural workers in which, modeled exposure estimates based on minimal historical data ranged between 100-400 ng/m^3.[122] In that study, there was large variability in diesel exhaust emitted among different types of off-road equipment as well as among exposures for farmworkers performing work. There was a lack of detail regarding the historical exposure scenarios, suggesting that these exposures reported may not be meaningful without better understanding of work tasks.

4.4.2 Nitrogen Dioxide

Nitrogen dioxide is typically correlated with BC, and we found that only three of 28 nitrogen dioxide samples (11%) were high enough to be detected with our sampling method (LOD = 0.02 ppm): 0.03, 0.04, and 0.10 ppm. These were worn by drivers who also had elevated BC concentrations. Participants A1, B1, and B2 wore the three detectable nitrogen dioxide samples and were also in the highest quartile of BC exposure. These participants were also driving older tractors for their full-shift (two Tier 0 tractors and one older tractor in the category of Tier 1, 2, or 3). None of those driving or working near Tier 4 tractors had detectable levels of nitrogen dioxide.

To our knowledge, this is the first study to measure nitrogen dioxide exposures among agricultural workers. Six studies reviewed by Pronk et al. measured nitrogen dioxide exposures among workers working near off-road diesel-powered equipment in the construction, dock and distribution, and airline industries. Resulting nitrogen dioxide geometric means ranged from 0.02 – 0.18 parts per million (ppm), providing an estimate of realistic exposures and what repeated sampling may reveal. Arithmetic means ranged from 0.02 – 0.32 ppm. Even among outdoor workers, where ventilation results in lower measured concentrations, nitrogen dioxide samples collected across the six studies (n=322) approached the TLV of 0.2 ppm for nitrogen dioxide. These results are higher than concentrations we measured among the three tractor drivers (0.03, 0.04, and 0.10 ppm, with arithmetic mean of 0.06 ppm). Although the PEL set by US OSHA for nitrogen dioxide is 5 ppm and the PEL set by California OSHA is 1 ppm, which are substantially higher than the samples we collected, research on health effects related to nitrogen dioxide exposure indicates that chronic occupational exposure to concentrations as low as 0.4 – 0.9 ppm may result in decreased lung function and immunological effects.[19–21]

Limitations of this sampling method included that some shifts were not long enough to get detectable results, which were limited by the passive sampling rate of the monitoring badge. The limit of detection for a 4-hour sample was 0.05 ppm and for an 8-hour sample was 0.025 ppm. The non-detected samples were less than 0.027 and 0.046 ppm based on their various sampling durations. We anticipated seeing higher exposures while designing these methods based on results from other studies of workers using off-road diesel-powered equipment. Active sampling methods could have been used to measure prevent non-detectable results and characterize lower concentrations. Nevertheless, this sampling method was able to detect as low as approximately 15% of the TLV and down to 2% of the California OSHA PEL, which is sufficiently sensitive.

4.4.3 Naphthalene, Phenanthrene and Anthracene

Although gasoline engines are reported to emit more NAP than diesel engines, NAP and PHE have been identified as predominant PAH compounds in some diesel fuels.[176,50] Few studies have measured NAP, PHE, and ANT in characterizing diesel exhaust exposure. Among both occupational and community-level exposure assessments, NAP and PHE are often the most abundant PAHs measured.[177,178] NAP has been widely measured in a variety of industries including creosote impregnation, coke production, iron foundries, aluminum production, and hazardous waste processing, in addition to occupational settings with burning wood, coal or railroad or traffic-related air pollution.[176,178]

We observed that drivers of tractors with high tailpipes and open cabs resulted in the lowest exposures to NAP, PHE+ANT, and BC. One farm had three closed cab tractors, which all had low tailpipes, and were Tiers 1-4. Based on the higher NAP and PHE+ANT concentrations for these tractor drivers, and high BC concentrations one of the tractor drivers, it is possible that engine exhaust may have leaked into the cab from underneath the cab prior to being exhausted out the tailpipe or that tailpipe emissions became trapped in the cab, due to low ventilation inside. Closed cab tractors may not be protective of air quality unless they are ventilated.
In a study of occupational exposure to PAHs among firefighters, personal sampling of 21 wildland firefighters resulted in a geometric mean concentration of 3,189 ng/m^3 and a maximum

concentrations of 21,439 ng/m^3 for NAP and geometric mean concentration of 210 ng/m^3 and a maximum concentrations of 2,867 ng/m^3 for PHE; ANT concentrations were 1-2 orders of magnitude lower than PHE.[179] These geometric mean and maximum concentrations measured are substantially higher than the results of our study (98 ng/m^3 and 8,392 ng/m^3) which was measured via the same analytical methods as our measurement of NAP. PHE and ANT in this study were also higher than our findings, and this may be due to a different analytical method used for measurement, which captured both gas-phase and particle-phase composition of these compounds.

Other occupational exposures of NAP have been reported that are also higher than the exposures we observed in our findings: median personal concentrations of 86,000 to 175,500 ng/m^3 for coke plant workers; and median personal air concentration of 61,810 ng/m^3 among workers applying coal tar asphalt sealant.[62] Reported mean exposures of 426 ng/m^3 and 371 ng/m^3 for asphalt workers and road construction workers, respectively, are in the same range as the mean concentrations we measured.[50] Phenanthrene has been measured at concentrations of 6,000 ng/m^3 among workers at a coal tar pitch loading and unloading depot,[49] 6,900 ng/m^3 among firefighters, and 15 ng/m^3 among post-fire workers.[180] A study of taxi drivers in urban regions of Korea indicated that taxi drivers had significantly exposures to NAP and PHE compared to non-taxi drivers.[181] Anthracene is a less commonly measured PAH.

The personal concentrations measured in our study (arithmetic mean of 398 ng/m^3 and geometric mean of 98 ng/m^3 for NAP, and arithmetic mean of 22 ng/m^3 and geometric mean of 17 ng/m^3 for PHE and ANT) are generally lower than those measured in other occupational settings. Due to the variability in ambient NAP concentrations based on urban environments, our results are higher than some ambient concentrations measured and lower than others.

Mean and median concentrations of NAP measured outside of homes in urban Northeastern U.S. cities were reported as 280 and 160 ng/m^3, respectively.[73] The median NAP concentration at a near-road monitoring location was very similar to the neighborhood concentrations: 150 ng/m^3. These results are lower than mean personal exposures we measured among farmworkers. However, mean ambient NAP concentrations measured in urban Southern California cities known to have higher rates of air pollution are generally higher than the mean concentrations we measured, ranging from 445 to 1,589 ng/m^3 in inland cities.[72] PHE has also been measured widely in ambient urban environments, generally at lower concentrations than NAP.[177,182] ANT concentrations measured in ambient environments are lower still than PHE.[9]

Our results are all below the California OSHA PEL is 500,000 ng/m^3 (0.5 mg/m^3), which is a legal exposure limit intended for occupational exposure. Given that NAP is a possible carcinogen, and there are no known safe thresholds of exposure to cancer-causing compounds, exposure should be reduced below this PEL for both workers and the general public. Health Canada recommends that the general public not be chronically exposed to NAP in indoor air above the limit of 10,000 ng/m^3 (0.01 mg/m^3).[183] The U.S. EPA has set a chronic reference concentration (RfC) for NAP in air of 3,000 ng/m3 (3 ug/m3). This RfC posits that a person can have chronic daily exposure up to this threshold over the course of their lifetime without appreciable risk of adverse noncancer health effects, and it is intended for the general public, including sensitive subgroups.[184] Among farmworkers in our study at some farms and using particular tractors, they may experience chronic daily exposures exceeding this RfC.

We measured these PAH compounds using the hydrophobic XAD-2 sorbent material which effectively captured gaseous molecules as they adsorb onto the sorbent. PHE and ANT predominantly exist in the gaseous state due to their relatively low molecular weight and high vapor pressure, but they can partition to the particle phase under certain atmospheric conditions.[185] Therefore, our measurement of PHE and ANT is limited to the gaseous-phase composition, and may exclude PHE and ANT in the particle phase. During analysis, front and back sections of the sorbent tubes were analyzed separately to rule out the occurrence of breakthrough. Given our measurement of PHE and ANT as a summary, due to the co-elution of these molecules during gas chromatography, it is difficult to compare our results directly to findings from other studies.

Background samples for PAHs resulted in arithmetic means of 22 ng/m^3 and 12 ng/m^3 for NAP and PHE+ANT, respectively, and geometric means of 18 ng/m^3 and 6 ng/m^3, for NAP and PHE+ANT, respectively. These results are significantly lower than personal samples collected in this pilot study. NAP background concentrations are substantially lower than ambient concentrations measured between 2019 and 2022 in Fresno, CA, which ranged from 15 to 6,739 ng/m^3, with an arithmetic mean of 555 ng/m^3 and a geometric mean of 324 ng/m^3. PHE+ANT background concentrations, on the other hand, were slightly higher than the ambient concentrations in Fresno, which ranged from 0 to 11 ng/m^3, with arithmetic mean of 2 ng/m^3 and geometric mean of 1 ng/m^3.[164] These differences between NAP and PHE+ANT are likely driven by the different composition of air pollution in the urban city of Fresno compared to the rural farm locations. Both NAP and PHE+ANT measurements were conducted via the same methods and lab protocols as those utilized for this pilot study.

4.4.4 Exposure Reduction and Implications

Although this study did not assess health outcomes, our characterization of exposure may inform future epidemiological investigations of farmer and farmworker health. Diesel exhaust is classified as a cancer causing compound, based predominantly on studies of miners, truck drivers, and railroad workers.[144,145] The Agricultural Health Study, a prospective cohort of over 40,000 participants, found that daily driving of tractors was associated with an increased risk of lung cancer among farmers.[147] In 2002, the US EPA summarized research on increased risk of lung, bladder, lymphatic, testicular, gastrointestinal, prostate, and kidney cancers, as well as multiple myeloma among people exposed to diesel exhaust at higher levels than those typically measured in the ambient environment, such as occupational exposures.[186]

Diesel exhaust is also associated non-cancer health outcomes, including adverse respiratory outcomes, including the exacerbation of asthma, adverse immune function and allergic response, and adverse cardiovascular outcomes.[187,188] In a cohort study of over 900,000 working individuals in Denmark between the years of 1995 and 2018, risk of heart attack associated with occupational exposure to diesel exhaust was determined among exposure and unexposed populations, controlling for demographics, comorbidities, socioeconomic factors, ambient air pollution, and other occupational exposures, including noise, stress, and job strain. Authors found a 4% excess risk of heart attack among populations exposed in the 50^{th}-75^{th} percentiles, and 8% excess risk attributable to exposure above the 75^{th} percentile, with recent exposure associated with an additional 7% higher risk in the highest exposed quartile for a total of a 15% excess risk attributable to occupational diesel exhaust exposure.[189]

The frequency of diesel exhaust exposure to farmworkers, particularly tractor drivers, may increase risk of adverse health effects. Job rotation is one strategy that has been utilized in other industries to reduce the risk of occupational injury and illness among employees (i.e., musculoskeletal strain and radiation exposure). Farmworkers experience cumulative impacts related to occupational exposures and social vulnerabilities. Studies among other occupational groups have reported that job insecurity is linked with work-family conflict and physical and psychological health outcomes among workers, including stress.[190,191] Participants' perception of increased work stressors was related to reduced parasympathetic activity in a sample of 653 healthy male workers and being in a heightened state of sympathetic arousal (i.e., "fight or flight") that is not balanced by the calming effect of parasympathetic activity (i.e., "rest and digest") results in an increased risk of adverse health outcomes.[192] Synergistic effects of stress and exposure to air pollutants has been studied among the general population, but not among occupational populations, nor among agricultural workers.[193,194] Assessing these co-exposures in combination is warranted given their potential interaction.

Although diesel-powered tractors have incredible endurance in their ability to run well for more than 20 years on average, proper maintenance including oil changes and diesel particulate filter cleaning are important ways to reduce excessive emissions. Unburned fuel (present in inefficient or old engines), lubricating oil, or burning of low molecular weight organic compounds in diesel fuel due to high temperatures are all causes of PAH generation in diesel emissions.[176] Therefore, ensuring proper functioning of engines with regular maintenance is another method to reduce exposures for workers. It was also observed that idling commonly took place across farms when there was a pause in the work task. Exposures could be reduced by turning the engine off.

As previously described in the introduction, CARB has funding and programs for farmers to receive financial support to purchase fuel-efficient Tier 4 or electric tractors. Even for farmers who know about available programs, barriers still exist to accessing grants, including time to write grants (which is directly proportional to financial stability), familiarity with government processes, and documentation and record-keeping for current equipment being replaced and future equipment received if awarded a grant. Education about grant programs as well as the local and regional benefits of reduced air pollution would benefit farmers and farmworkers, as would access to grant-writing assistance.

4.4.5 Limitations

Climate and temperature can have a significant effect on diesel exhaust exposures for some jobs.[115] Temperature and relative humidity affect PAH concentrations in the atmosphere.[50] A limitation of this investigation is that we were not able to measure daily or real-time temperature in the sampling locations on farms. We were also not able to download measured temperature or weather data post hoc from data collected by the National Oceanic and Atmospheric Administration (NOAA) because there was no data collected near the farm locations. Daily variability observed in BC measurements is likely driven by different weather patterns throughout each day and across days as well as differences between farm locations.

The specific crops grown on these farms, the size of the farms, and the nature of organic farming likely resulted in work tasks at these farms that were generally more labor intensive than other agricultural operations in the country, for example corn, soy, or wheat. A significant attempt was made to recruit farms in the San Joaquin Valley because it contains over 50% of California's agricultural equipment;[7] however, we able to recruit only one participating farm from this region. It was important to get buy in from employers to prevent any employer retaliation among participating employees; however participating employers may not be representative of other agricultural employers. This study is subject to selection bias and the Hawthorne effect. The population of participating farms and farmworkers was selected by convenience sampling, and we gained consent from employers to recruit participants onsite. There could be systematic differences in the work conditions or practices on the participating employers compared to other farms that were not willing to participate. Although approximately 90% of the employees we contacted consented to participate in the study, there may additionally be systematic differences between workers willing to participate versus workers who were unwilling to participate.

Nevertheless, measured diesel exhaust exposures are likely generalizable among farmworkers in the country working with similar crops. Diesel-powered agricultural equipment is ubiquitous in agriculture, and exposure has remained relatively invisible because associated health effects are often delayed, varied, or undocumented.[128] This pilot study was not intended to be representative of all farmworkers, but to provide information about diesel exhaust exposure concentrations specifically among farmworkers working around diesel-powered equipment.

Limitations of our monitoring methods include our inability to detect nitrogen dioxide at concentrations below 0.02 ppm; however, this concentration is still 15% of the TLV. We measured PHE and ANT in the gas-phase only; these compounds primarily exist in the gas-phase, however there may have been a small percentage (~10-20%) of these compounds lost during sample collection.[9,195] Microaethalometer filter change outs represented an opportunity for measurement bias. Sampling error can occur when a new, clean filter is inserted, resulting in very low attenuation values (very small changes in light transmission between measurements), and subsequent increased scattering interference or Low Signal-to-Noise Ratio. Sampling error can also occur when loaded filters result in an underestimation of BC because the laser can no longer accurately measure BC on the filter spot, known as a "shadowing effect". Both types of sampling error negatively bias BC measurements. The need for changing filters between microaethalometers varied; therefore, some between-monitor variability resulted from non-coordinated filter change outs. We evaluated between-monitor variation and found that differences by microaethalometer did not contribute to the variability in the data or affect model results. Lastly, while the flow rate of 0.1 L/min was needed to achieve effective collection of $PM_{1.6}$ with the microcyclone, it may have introduced noise, increased instrument sensitivity to rapid environmental changes, and thus the increased the detection of negative values, because fewer particles were pulled onto the filter at this relatively low flow rate.[160]

4.4.6 Implications

The hierarchy of controls asserts that exposures should be eliminated whenever possible, and if not possible, exposures should be workers should be reduced. Based on the hierarchy of controls and the principle that there is no safe threshold of exposure for carcinogens, diesel exhaust exposures should be prevented or reduced as much as possible. There is also a risk of non-cancer health effects related to chronic diesel exhaust exposure among farmworkers, including adverse respiratory, cardiovascular, metabolic, and immune function outcomes. This pilot investigation identified opportunities for diesel exhaust exposure reduction among farmworkers. Breaks should be taken away from running or idling diesel-powered equipment whenever possible. Tractor drivers should turn off engines rather than idling when possible. To the degree possible during planting and harvesting tasks that require walking near a tractor, distance should be increased to reduce proximity to the tractor tailpipe. Moving the location and directionality of tractor tailpipes by a trained tractor mechanic may reduce exposures to drivers or other nearby workers, as observed in this study. Closed cabs, unless equipped with a positive pressure ventilation system, may not be protective of diesel exhaust exposure. Engine maintenance, such as regular oil changes and cleaning of diesel particulate filters, may reduce diesel exhaust emissions or some of its associated air pollutants. Use of the additive DEF in some tractors may also reduce some diesel exhaust emissions, such as nitrogen dioxide. Lastly, tractor manufacturers may consider exposure to the user when designing the tailpipe location and directionality on their diesel-powered products.

Although incentives are available to employers who replace polluting off-road diesel equipment from local, state, and federal government agencies, most farmers and farmworkers were not aware of these opportunities. Newer, less polluting Tier 3 and 4 diesel engine tractors or electric tractors can be purchased using government subsidized grants to reduce exposure for farmers and farmworkers. Electric tractor technology is advancing rapidly and two large-scale agricultural manufacturers (John Deere and New Holland) have released electric models.

The federal OSHA issued a Hazard Alert related to adverse health effects of diesel exhaust exposure in 2013; however, they have not developed a PEL nor a way to regulate diesel exhaust exposure outside of mining industries. This data can inform future epidemiological and industrial hygiene investigations, insights about the regional contribution to air pollution from agricultural equipment, and policy initiatives and exposure recommendations related to diesel exhaust.

4.5 Conclusion

This pilot study provides new information about farmworker exposures. Our findings indicate that farmworkers are more highly exposed to constituents in diesel exhaust than the general public and farmers. Task, tractor age (Tier), tractor cab style and tailpipe location were the primary factors impacting exposure concentrations. Driving diesel-powered tractors was associated the highest exposures in this study; however, walking near or behind tractors to plant or harvest was also associated with elevated exposures for PAHs. Tasks involving older tractors and closed cab and low tailpipe tractors in this study were associated with higher concentrations of BC, PAHs, and nitrogen dioxide. Diesel exhaust is a known carcinogen and exposures should be reduced as much as possible. This pilot investigation identified opportunities for reduction of diesel exhaust exposure among farmworkers and barriers to utilizing the equipment replacement grants among farmers.

Chapter 5. Communicating Diesel Exhaust Exposures Among Farmworkers: An Evaluation of Participant-Informed Report-Back Materials

5.1 Introduction

5.1.1 Background

Researchers have studied and advocated for the process of returning environmental health study results to individual participants, herein referred to as "report-back", since the late 1990's.[35,196] A 2018 report by the National Academies of Science, Engineering and Medicine (NASEM) recommended that report-back be performed in most studies, averring that participants' right-to-know about their own data, low risk of harm, and potential benefits outweigh withholding the return of individual results.[197] Although uncertainties regarding the clinical significance of individual-level results, such as chemical exposures, had historically been pointed to as a potential ethical barrier for report-back of personal exposure results, researchers have demonstrated that study participants want access to their personal results, even if their health implications remain uncertain.[37,198,199] Potential benefits of report-back include increased environmental health literacy (EHL) and elucidating exposure reduction strategies that participants can undertake.[200,201] EHL incorporates concepts about how people seek out, comprehend, evaluate, and use environmental health information to make informed choices and prevent or reduce exposure for themselves or their community.[40] Not only can report-back empower individual participants, it can also benefit researchers by building trust with participants, leading to community-engaged research, and possibly increasing environmental health awareness among the general public.[202] Although returning results to study participants has become increasingly common, report-back methods are highly variable. [203,196,204]

There are various methods by which researchers return exposure results to study participants, the most common being mailing hard copies or emailing electronic documents that describe exposure results.[37] Researchers typically develop their own report-back documents, including graphics and data visualizations, which present not only a source of variation in report-back practices, but also a significant barrier to returning results due to the financial, technical, material, and institutional resources needed.[196] Some researchers have taken this a step further by hosting group meetings where participants can discuss their individual results in-person with researchers and engage with other study participants.[204] The Silent Spring Institute developed the Digital Exposure Report-Back Interface (DERBI), which allowed for efficient development of report-back among researchers and personalized, interactive and convenient report-back for participants, which could be accessed on computers or smart phones.[41] To address the wide variety of report-back practices and methods, researchers have suggested sharing of methods, frameworks and tools to allow for replication and adaptation of report-back methods across studies and participant populations. Korfmacher and Brody proposed a framework for institutionalizing report-back, including clear guidance on report-back content and timing, training for researchers, reviewers and institutional review boards, and establishing resources for cost-effective tools and shared report-back infrastructure.[196]

5.1.2 Report-Back Best Practices

Another source of variation is the audience-specific communication for individual study populations. Best practices on report-back have been evaluated by interviewing participants after they received their study results. Guidance from most research evaluating how participants understand and feel about their exposure results points to the importance of contextualizing exposure information, for example, explaining what is known and unknown about the meaning and potential clinical impacts of exposure, and providing support for individuals to interpret their results.[197] According to a 2014 study from Brody et al., "meaningful report-back includes contextual information about health implications and exposure reduction strategies".[35] The *Personal Exposure Report-back Ethics* (PERE) Study conducted interviews with 54 participants who participated in three different environmental health studies and received their study results to collect information about report-back preferences and perspectives. This effort, along with a workshop to gather information from report-back experts and stakeholders, allowed researchers to compile best practices, such as: including both text and graphics in report-back materials, explaining why researchers are studying these chemicals, and what is known and unknown about associated health risks; including information about how people can reduce their exposures; and reporting study-level or community-level findings to help participants put their individual results into context.[1,4] Additional best practices cited in the NACEM report include setting expectations during the consent and enrollment process about what kind of information will and will not be made available in report-back materials and that personal exposure data cannot be linked to individual health outcomes; it is important to communicate the limitations in what is known about "safe" levels of exposure given that many chemical exposures are measured in a research capacity, and lack adequate health outcome information, regulatory benchmarks, or validation of effective exposure reduction strategies.[197]

Report-back communications should be also appropriate for participants with different backgrounds.[197] Researchers emphasize the importance of using appropriate methods to deliver results clearly.[205] Tomsho et al. also developed and evaluated a framework in which they defined effective report-back as involving engagement, understandability, and actionability for participants.[204] "Failing to ensure accessibility of materials may disenfranchise" participants with lower literacy or numeracy skills, "and may perpetuate health disparities by continuing to keep environmental health information out of reach for those who are vulnerable".[34] Best practices have been recommended in the body of literature on report-back from the last two decades, however Korfmacher and Brody reported in 2023 that report-back has still "not been fully developed, disseminated, and implemented across the environmental health research enterprise."[196] Castillo et al. published similar results in 2025 from 20 expert panelists surveyed on their perspectives of report-back ethics, including exposure scientists, community engagement specialists, public health researchers, clinicians, and ethicists; results converged on a need for report-back harmonization. Specifically, they reported a need for standardized terminology, particularly regarding the relevance of results to individual health, behavior and knowledge.[206]

Researchers have previously engaged participants to inform the development of report-back materials given the unique aspect of report-back messaging and exposure reduction strategies for distinct study populations. In a study of manganese exposure in rural Appalachia, community members were engaged to inform the development of report-back materials and helped develop easy-to-interpret data visualizations and graphics.[42] Oksas et al. conducted focus groups with 18 pregnant participants from the *Environmental influences on Child Health Outcomes* (ECHO) research program to learn about report-back preferences and perspectives and inform the design of report-back materials for the larger study population; they learned that participants wanted exposure reduction guidance and that they were motivated to make changes to protect the health of their families and communities.[207] Several other researchers have also assessed the usability and accessibility of report-back materials via usability-testing. Perovich et al. engaged study participants of the *Green Housing Study* to provide feedback on report-back materials through semi-structured interviews, prototype testing, and community meetings.[208] To develop evidence-based best practices for report-back formatting, Tomsho et al. created report-back templates that were rated by members of the research team and a community partner organization using the CDC Clear Communication Index and other quantitative tools.[34] This work added to the report-back literature by demonstrating methods for readability that can be used in the development of report-back materials. A limitation of this study was the lack of *post hoc* evaluation by the participants themselves, who would be best positioned to evaluate the readability of the report-back templates. Additionally, the literacy demand tool used by the authors called the Simple Measure of Gobbledygook (SMOG) is also only appropriate for evaluating the reading level of text in English. Though generalizability of findings may be limited, these investigations provided important information about how different study participant populations understand their report-back, what they are motivated by, and what they find useful.[207]

All of the previously mentioned study populations were composed of members of the general public. Some investigations have interviewed participants of diverse backgrounds about their report-back perspectives or conducted interviews and community meetings in Spanish; however, with the exception of these participants within the ECHO and PERE Study report-back interviews, the majority of report-back study participants skew toward more being highly educated, more affluent, and more likely to be white.[37,204,209] Farmworkers are not well-represented in the report-back literature.

5.1.3 Report-Back in Occupational Studies of Farmworkers

A total of three studies have investigated report-back materials and methods in occupational populations.[209–211] Two of these studies engaged farmworkers during the return of their individual-and household-level pesticide exposure results. Both of these studies involved study participants in the design of report-back materials, which aided in participants' comprehension and usability of the information, and suggesting that "it is possible to adequately convey complex scientific findings in a way that is useful and accessible to those without a scientific background or formal education."[209] In one of these investigations, interviews were conducted with study participants to assess the effectiveness of the report-back process after data had been disseminated. Interview results demonstrated that a sizable proportion of participants (approximately 70%) correctly interpreted their pesticide exposure results and were able to explain them to the interviewer; the majority of participants (approximately 97%) also remembered effective ways to protect themselves from pesticide exposure, indicating they learned these strategies from the report-back materials.[210] Even when the reported pesticide concentrations lacked certainty in regards to a level of exposure that would be "safe" and a specific level that would be "dangerous", authors found that participants readily understood the information and shared it with others.

In addition to many occupational exposures that farmworkers face, such as pesticides, heat and dust, diesel exhaust presents a significant yet often overlooked hazard. Compliance exposure monitoring in occupational settings is conducted for hazards with established regulatory exposure limits.[113] Diesel exhaust is classified as a carcinogen, and presents many other health risks to the respiratory, cardiovascular, and immune systems.[166] Although diesel exhaust exposure is prevalent in many workplaces, with the exception of the mining industry, there are no occupational exposure limits for diesel exhaust in other sectors in the United States.[212] According to the federal Occupational Safety and Health Administration (OSHA), exposure results must legally be made available to workers; however, in practice they often are not provided unless requested by employees and are not typically explained in detail by employers or other experts. The pilot study presented in Chapter 3 was the first study to quantitatively assess exposures of diesel exhaust constituents among farmworkers. There is still uncertainty among researchers about the best methods for reporting study results to vulnerable populations, for example participants in low-resourced settings with little ability to protect themselves from exposures, which may include occupational cohorts.[198] Further, more information about best practices of environmental health report-back among occupational groups, and specifically farmworkers, is warranted.

Risk communication about diesel exhaust is challenging due to its ubiquitous nature. Its associated health effects are often delayed, varied, or undocumented. A qualitative study was performed to understand perceptions among workers exposed to diesel exhaust in the transportation, firefighting, fishing, construction, and health services sectors in Canada; all thirty participants reported never receiving health and safety training specific to diesel exhaust at their workplace, and wanted training and personal protective equipment to be provided by their employer.[128] Some occupational groups may represent populations in which it might be difficult for workers to mitigate exposures individually. Farmworkers, in particular, are considered a vulnerable population due to their varied occupational exposure risks and many documented health disparities.[127] Nevertheless, failing to engage farmworkers directly about the results of the diesel exhaust investigation would undermine efforts to empower them with exposure information, with the ultimate aim of reducing health disparities.

We interviewed participants to explore attitudes of exposure, safety at work, and accessibility of exposure results. Aims of this investigation included exploring: participants' perceptions of the accessibility, clarity, and usefulness of results-return communication; how formatting, language, and content aided or detracted from understanding; and whether a short explanatory video aided understanding of the report-back document. To our knowledge, this pilot investigation is the first to perform diesel exhaust exposure report-back evaluation among farmworkers. This work builds on the growing body of literature on report-back and fills a gap about how diesel exhaust exposure results information can be successfully returned to this population.

5.2 Methods

5.2.1 Farm and Farmworker Study Population

An effort was also made to recruit farms that were representative of farms and labor contractors in California, including organic and non-organic and small to large-sized operations, operations in San Joaquin Valley, which contains over 50% of California's agricultural equipment, and farms growing the most highly produced crops in California: strawberries, grapes, nuts, apples, lettuce, and tomatoes.[7,213] Recruitment of farms was conducted through word of mouth, attending workshops and conferences, internet research, and connecting with farmer stakeholder organizations such as farmer advocacy organizations, agricultural alliances and research groups, and farmer's market associations. A total of 25 agricultural operations and 6 farm stakeholder organizations were approached to recruit employers. A total of five employers of agricultural operations participated in the pilot study; they grew apples, stone fruit, diversified vegetables, wine grapes, and table grapes in the counties of Mendocino, Yolo, Contra Costa, and Fresno. Four of the five employers owned small- to medium-sized organic farms and one employer was a labor management company.

Farmworkers were recruited at these 5 locations in Northern California where employers granted researchers access. Study inclusion criteria consisted of non-smoking participants above 18 years in age who spoke English or Spanish. Recruitment entailed talking to farmworkers at their work sites to see if they were interested in participating in the ACRE Pilot Study; they were shown lightweight vests holding personal exposure monitoring devices that would be worn if they participated. They were informed about the purpose and the confidentiality practices of the study prior to signing a written informed consent document. All study protocols were approved by the Institutional Review Board (IRB) at the University of California, Berkeley (Protocol ID 2023-09-16692).

Farmworkers and two farmers on small farms performing work representative of farmworkers (n=29) consented to participate in the study and wear personal exposure monitoring devices to measure three constituents of diesel exhaust for their work shift **(Chapter 4).** Farmworkers had the opportunity to participate in personal exposure monitoring for more than one day if they wanted to, and some participated up to four days. A subset of farmworkers (69%) participated in work-related interviews based on their interest and availability (n = 20) **(Figure 1).** The terms farmworker, employee, and participant are used interchangeably.

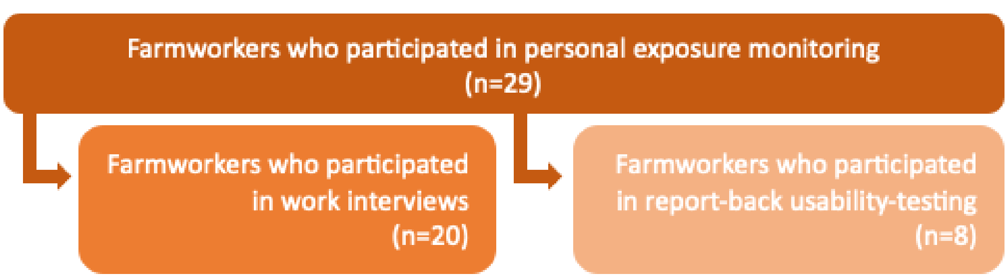

Figure 9. *Schematic showing how many farmworkers participated in personal exposure monitoring, work interviews, and report-back usability-testing interviews.*

5.2.2 Interviews Exploring Work Practices and Attitudes of Exposure and Safety

Qualitative semi-structured work interviews were conducted to explore participants' attitudes about diesel exhaust exposure, work tasks, occupational health and safety, whether participants wanted to receive their study results, and if so, what they hoped to learn. Items from the validated Perceived Stress Scale and Migrant Farmworker Stress Inventory were included in the semi-structured interview guide.[109,124] The interview guide was translated to Spanish and tested with Spanish-speaking and farmworker populations prior to deployment in the field. The majority of participants chose to be interviewed at their work site, with some requesting interviews at their home or at a public park.

5.2.3 Report-Back Design

Work interviews informed the design and content of report-back materials. Participants were asked what they would like to learn from report-back and what kind of in format they would like to receive the information. Design of report-back materials was also informed by the Silent Spring Institute's DERBI platform, Biomonitoring California's report-back documents, and other research publications outlining best practices for effective report-back.[34,207,214] Our report-back materials **(See Figure C1 and C2)** contained the following components: graphs of individual and study group exposure concentrations, comparisons to other exposed populations from investigations using the same methods to measure black carbon (e.g. background concentrations in Fresno, CA, professional drivers, railroad workers), accessible information about health implications of diesel exhaust exposure, and what employees and employers can do to reduce exposures.

5.2.4 Report-Back Usability-Testing Interviews

Participants who already consented to being recontacted in the initial informed consent were recruited to participate in usability-testing interviews. These farmworkers who already participated in personal exposure monitoring (n=29) were randomly recruited via phone calls and text messages to evaluate the usability, accessibility, and understandability of study results. Participants who responded then participated in usability testing interviews (n=8) **(Figure 1).** Researchers set up one-on-one in-person meetings with participants based on their availability; interviews were conducted at the participants' worksites or homes. Five farmworkers had previously been interviewed and three had not.

Usability-testing explored participants' perceptions of the usability, accessibility and understandability of report-back materials. During the meetings, a researcher interviewed the participant after they read through a printed report-back document containing example diesel exhaust exposure results. Qualitative semi-structured interview guides were developed based on exposure report-back research (**Figure C1**).[34,35,37,215] We also adapted a positively-scored version of the usability survey called the validate System Usability Scale that was evaluated and published in 2021.[215–217] A 5-minute video was also developed in the online platform Canva, in which stock video clips of tractor use were paired with animated images of graphs from the report-back document. The report-back document was translated to Spanish and tested with

Spanish-speaking populations prior to deployment in the field. The text from the hard copy report-back document was used to narrate the video in Spanish. The video can be found here: https://www.youtube.com/watch?v=Y7syXo-kg00

During the interview, participants were asked to rank their agreement with following statements on a Likert scale: I thought the document was easy to understand; and, I think I could use this document without the support of a scientist. Participants were asked what they found clear and unclear to understand on the document and why, as well as which graphs, they preferred and why. Researchers asked participants to point to language, graphs, or pictures that were clear or unclear on the document. Researchers also explored participants' understanding of how they interpreted their own results compared to those of other workers on the graphs. The 5-minute video was then shown to participants on the researcher's phone. Participants were asked to rank their agreement with following statements on a Likert scale: I thought the video made the document easy to understand; and, I think I could use the video and document without the support of a scientist. Researchers asked participants whether the video helped them to understand the report-back document and why. Participants were also asked: how they might use the information in the report-back document and video; whether they planned to change any work behaviors related to reducing exposure; whether they felt other farmworkers and employers could implement the recommendations in report-back document and video; to rank their concern about health effects related to diesel exhaust on a Likert scale; and if their attitude about healthy and safe work conditions for farmworkers. All interviews were conducted in Spanish.

Data was analyzed on an ongoing basis as described below. After receiving feedback from four participants during individual usability-testing interviews, results reached saturation in the areas of graph preferences, feedback on text and language, and the usability of the video. Saturation refers to the point in qualitative data collection when no new information is gleaned from continued collection.[218] We then edited the report-back materials based on the feedback from these four participants. Additional participants were then recruited to provide feedback on the revised report-back materials. After another four participants were interviewed, their feedback converged on the topics of language and graph preferences and the usability of the video. Given that saturation was reached, participant recruitment for more interviews did not resume after eight participants were interviewed from four of the five participating farms.

5.2.5 Analysis of Interview Data

Interview data was analyzed via Rapid Qualitative Analysis (RQA), as described by Hamilton and Finley and evaluated by Taylor et al.[125,126] According to rigorous best practices of RQA, qualitative data from participant interviews was deductively compiled into structured templates that were pre-determined based on interview guide items. Two different research analysts analyzed work interview data to establish reliability of the data analysis and validity of the emerging themes. Due to resource constraints, one researcher analyzed the report-back usability testing interview data.

5.2.6 Report-Back of Study Results

Upon conclusion of the study, employers were offered study results including farm-level and tractor-specific data. Farmworkers were asked during the informed consent process if they wanted to receive their study results. After receiving feedback and performing iterative updates on report-back materials during usability-testing, the finalized report-back document and video were sent to all farmworkers who elected to receive them.

5.3 Results

5.3.1 Summary of Participant Information

The ACRE Pilot Study collected 50 personal air samples of constituents in diesel exhaust among 29 participants employed by four farms and one labor contractor in northern California from April - September, 2024 **(Table B1).** Twenty-eight percent of participants were female and 72% were male. Ninety percent of participants spoke Spanish as their primary language and were from Mexico, Guatemala, Honduras, and Peru. Participants' ages ranged from 21-75, with a median age of 37 and an average age of 40. The number of years that farmworkers had worked for that employer ranged from less than a year to 17 years, with a median of 1 year and average of 4 years. The two farm owners had been working on the farm for 40 and 53 years. Ninety three percent of participants (100% of those whose titles were farmworkers) identified as Latino/Hispanic, and the two farm owners identified as White and Asian. Twenty-seven (93%) farmworkers in the study worked on an organic farm.

5.3.2 Attitudes Informing Report-Back

Report-back documents were informed by attitudes and perceptions expressed during participant interviews. Quotes were included in the original language of the participant. Quotes in Spanish were translated to English. Additionally, participants are referred to using gender-neutral pronouns to keep their information as confidential as possible.

In addition to being asked during the consent process if they would like to receive their personal exposure monitoring results, participants were also asked during interviews what they would like to learn from their results. During the consent process, 26 people (89%) said they would like to receive their personal exposure monitoring results. Among the 20 participants interviewed, most people (18 out of 20, or 90%) also wanted to receive their results. The two people who did not want them saw no benefit of receiving them, and one person mentioned not knowing what they would learn from them. People were primarily motivated to receive their results because they were curious how much diesel exhaust they were exposed to, or if their exposure would be considered elevated (45%) and whether the exposure could affect their health (30%).

"Aprender de lo que podemos prevenir y lo que no podemos prevenir…Sabiendo de que... cuanto afectaría nuestra salud con el trabajo que hacemos, y tanto el humo de la máquina, entonces pudiéramos aprender cómo evitarlo…"

> *"To learn what we can prevent and what we can't… knowing how much our health would be affected by the work we do and by the smoke from the tractor, then we could learn to avoid it."*

Two people also wanted to understand what the results meant in the context of the study and what the study results were overall. Eight people (40%) expressed not knowing what to expect from their results, but most of them still wanted to receive the results, with one person specifically saying they thought they would not understand the results.

"La información que me pueden mandar, para saber no más. Yo no sé lo qué van a decir… porque yo no lo voy a entender."

> *"Whatever information you can send me, just to know. I don't know what it will say… because I'm not going to understand it."*

When asked how participants would like to receive their results most people requested them via hard copy in the mail, with a few requesting electronic copies via email or via text. When asked about their perception of diesel exhaust, half of participants (10 out of 20) said they had never thought about it before or did not really notice it. The other half of participants expressed smelling it or having a general awareness of it. Among them, 8 people (40% of all participants) were specifically concerned about exposure for health reasons, particularly long-term exposure. Six people reported noticing the diesel exhaust smell while working near tractors; four of them felt it was bothersome and reported getting headaches, coughing, or feeling ill after smelling it. One person reported getting headaches after driving the tractor because of the smell of the exhaust and the noise and heat from the tractor.

"A veces si, se siente bien fuerte cuando inhalamos. A veces lo hace toser a uno."

> *"Sometimes, yes, it feels intense when we inhale it. Sometimes it makes you cough."*

"…No sé qué consecuencias tenga al largo plazo o corto plazo, pero me imagino que enfermedades de la respiración o los pulmones… después de muchas horas de exposición."

> *"I don't know what kind of long-term or short-term consequences it can have, but I imagine respiratory or lung diseases… after many hours of exposure."*

Participants expressed implicit awareness of exposure reduction methods when describing their exposure experience and the degree to which they felt concerned about diesel exhaust. One person expressed concern about the frequency of their exposure.

> *"Podemos pensar que un solo tractor no puede afectar tanto, pero es un tractor… que se usa todos los días. Creo que yo paso más tiempo en un tractor que durmiendo en un día, así que es bastante la contaminación."*
>
> > *"We can think that just a single tractor can't affect someone that much, but it's a tractor that… you use every day. I think I spend more time on a tractor than sleeping in a day, so there is a lot of pollution."*

Others said they were not concerned about diesel exhaust because of the infrequency of their work around tractors (4 people), the distance they work from tractors (3 people) and the short duration of exposure (1 person).

> *"Si estuve olido todos los días, tuviera más mal."*
>
> > *"If I smelled it every day, it would be worse."*

Two people reported that they had noticed a difference in the amount of diesel exhaust they inhaled or smelled with the distance they were from the tractor depending on the type of crop they harvested. Additionally, two people felt protected from diesel exhaust exposure by the closed cab of the tractor and two others expressed that well-maintained tractors produce less exhaust. Lastly, two participants noticed a difference in the amount of diesel exhaust they were exposed to with different tractors they used, based on the location of the tailpipes.

When asked specifically about their knowledge of reducing or avoiding exposure to diesel exhaust, 15 participants overall (75%) expressed awareness of one or more factors that could increase or decrease exposure to diesel exhaust. These ideas included maintenance of tractor engines (8 people), the age of the tractor or using newer tractors (5 people), respiratory protection (5 people), the amount of time working near tractors (6 people), distance from tractors (5 people), acceleration of tractors while driving (1 person), and filters on the tailpipe (1 person).

> *"Uno no puede resistir mucho humo que está pegando la cara. Cuando el cuerpo de uno siente que el aire del tractor se afecte, entonces, mejor que apartes o alejas… mejor retirarse."*
>
> > *"You can't withstand a lot of smoke that's hitting your face. When you feel the tractor exhaust affecting you, then it's best to move away… it's best to take a break."*

Five people didn’t know how to reduce their exposure, with one person suggesting that not using diesel-powered tractors would be the only thing they could think of. Three people (15%) additionally expressed awareness that diesel exhaust can harm the environment or contribute to climate change because of the impact on regional air pollution. All five participating farms were organic farms, and three participants (15%) expressed gratitude that they worked on organic farms and did not have to work with chemicals.

> *"Pues aquí no usa químicos, o sea químicos naturales, no les hacen daño, pero si en otros ranchos."*
>
> > *“Here we don’t use chemicals, but we use natural chemicals, they don’t harm you, but at other farms, they do use chemicals.”*

5.3.3 First Round of Report-Back Usability-Testing Interviews

After preparing results return materials, we conducted report back interviews to test the usability, accessibility, and understandability of the document and video. During the interview, participants were presented with hard copies of the results return document and watched the video on the interviewer’s phone. Seven of the interviews were conducted in Spanish, and one was conducted primarily in English with some Spanish spoken as well. After the first four interviews, saturation was reached on the following themes: graph preferences, the usefulness of the video, and exposure reduction measures.

All four participants preferred bar graphs instead of scatterplots **(Figure 2).** The video helped them understand how to interpret both types of graphs, and specifically what was being shown in the scatterplot. After watching the video, one participant said they could see how the scatterplot provides more information than the bar graph, that the scatterplot includes exposure information about all employees in the study and how that compares to the individual participant’s result; however, the bar graph includes only the median and the maximum compared to the individual results. Even after watching the video, all four employees felt that the bar graph was clearer and simpler to understand.

All four people also said that the video helped them understand the information in the results document, both in terms of understanding the graphs and feeling more confident about the chemicals in diesel exhaust and exposure reduction measures. After reviewing the report-back document and video, all four people were able to list or explain exposure reduction measures that they could implement, including turning off tractors instead of idling, distancing oneself from tractors when possible, sharing this information with other farmworkers, and wearing masks. All four participants expressed that farmers and employers could or should share this information with farmworkers to increase awareness. Two of them also felt that farmers and employers should maintain tractors regularly to prevent additional air pollution in the tractor emissions and provide personal protective equipment (PPE) like masks or respirators.

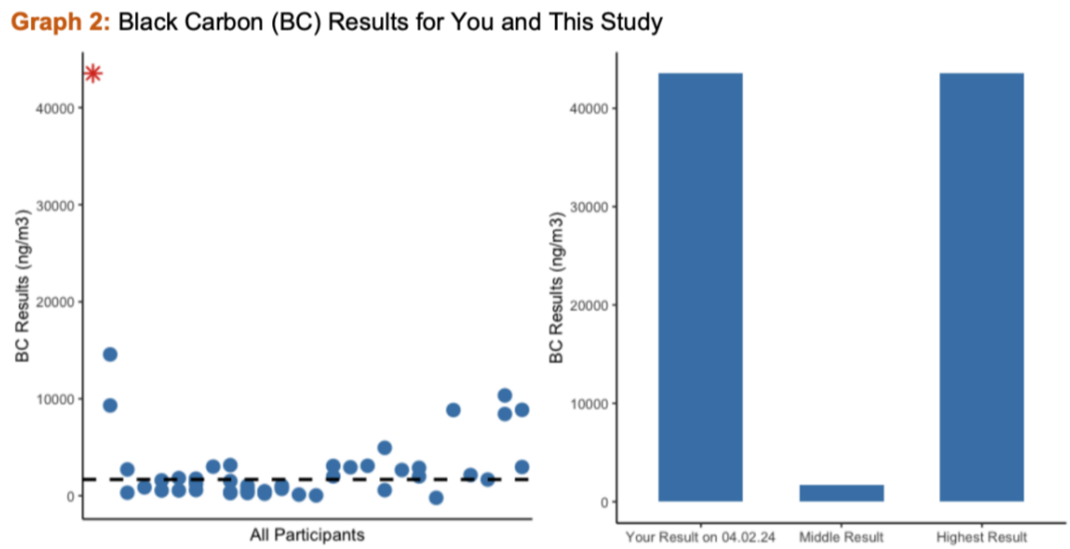

Figure 10. *This scatterplot (left) and bar graph (right) were included in the first iteration of the report-back document, and participants were asked which they preferred. An anonymous participant's results were reported in the report-back document as an example. In the scatterplot on the left, the red star shows the hypothetical participant's black carbon result; blue dots are the black carbon results of other participants in the study. The black dashed line shows the median concentration. In the bar graph on the right, median and highest result of other participants in the study is shown as separate bars for comparison to the hypothetical participant's result in the bar on the left.*

Two participants felt concerned about the potential health effects of diesel exhaust, one felt a little concerned, and one felt unconcerned. One participant reported that they would like to use a filtering facepiece respirator if they were provided by their employer. One participant expressed concern that farmworkers are exposed to diesel exhaust and cannot just get another job, but felt more secure knowing about these exposure reduction measures, which they believed were tangible and realistic for farmworkers in general to implement. Another participant was not concerned about diesel exhaust because they did not frequently work around it, but expressed knowledge that the organic spray being used on the farm had a strong odor and could be toxic. Similarly, two other employees expressed concern and awareness of other work hazards including noise from tractors and valley fever, a lung infection caused by naturally occurring fungus in some soils that can cause serious illness or death.

> *"Hay riesgos en muchos trabajos, pero hay que reducirlo por la manera posible"*
>
> > *"There are risks in many jobs, but it's important to reduce them whenever possible"*

Participants recommended changing specific aspects of the results return document. One participant requested changes to the graphs for clarity, including larger text on the x- and y-axis labels, using the word "amount" instead of "results", and spelling out the name of the chemical each time, because they found the acronym to be confusing. Another participant felt that the language in the “Summary of your Results” section on the bottom of page 1, when referencing results in the top or bottom 50% of the data was repetitive, and a little unclear. Two participants wanted to know more information about why some workers had higher results than others. Lastly, one person was confused by the colors used on the line graph, assuming that green indicated a safe level of exposure.

Changes were made to the results return document to remove the scatterplots, use larger font and clearer axis labels on graphs, change the color scheme on the line graph, remove text in the “Summary of Your Results” section, increase the use of graphics to convey information, and include low-text information about the factors influencing higher results among farmworkers in the study and how the study results compared to other studies. The video was edited to reflect the updated document.

5.3.4 Second Round of Report-Back Usability-Testing Interviews

After editing the report-back materials, more participants were recruited for usability-testing interviews. Saturation was reached on the following themes after conducting four interviews: the video helped participants to understand the updated results return document, particularly for the graphs; participants understood exposure reduction measures, citing at least one example of ways to reduce their own exposure and how farmworkers in general could reduce their exposures on their own and with the help of their employers. When asked for feedback on what could be improved, no one suggested changes to the text or graphics. All four participants expressed that the graphics displaying information, such as **Figure 3**, were helpful for them in understanding the document. Three of the four participants expressed a bit of confusion about the bar graphs showing their individual-level results compared to the study population until they watched the video, reporting that the video helped them feel more confident in interpreting the graphs.

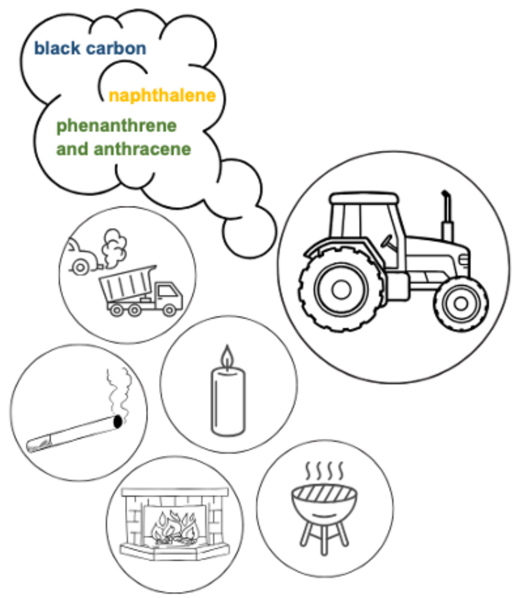

Figure 3. *Graphic showing that black carbon, naphthalene, and phenanthrene and anthracene come from diesel-powered tractors as well as other sources*

After changing the colors on the line graph to indicate green as the lowest exposure and red as the highest exposure, participants generally found the updated color scheme helpful in interpreting the line graph **(Figure 4).**

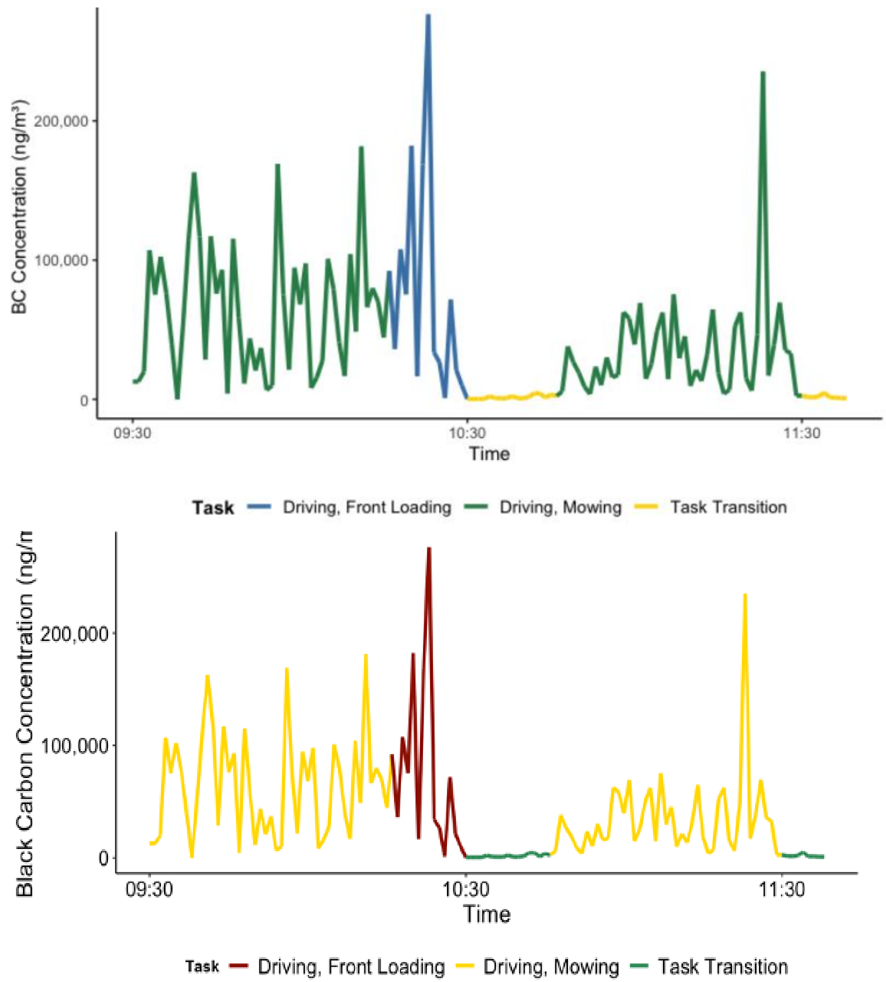

Figure 4. *Line graphs included in the first (top) and second (bottom) iteration of the report-back document.*

Two out of the four participants interviewed in the second round of interviews expressed concern about the potential health effects of diesel exhaust. They felt worried about the risk of cancer or respiratory issues, like the worsening of asthma, developing from long-term exposure to diesel exhaust. Before seeing the results return document, they did not know about health implications associated with long-term diesel exhaust exposure, and they appreciated learning about them. One person also said that they earned one more dollar an hour to drive a tractor, which although was not substantial, was helpful in making more money, but they expressed a dilemma that they now realized they were more highly exposed as a tractor driver than if doing other farm work tasks.

> *"Es preocupante, el cáncer"*
>
> > *"Cancer is worrisome."*

> *"I don't know what will happen in 10… 15 years."*

The two other participants expressed that they were previously familiar with the fact that inhaling smoke could affect one's health, and they were not surprised to see the listed health effects associated with diesel exhaust exposure. They both expressed that they were "not worried" or "not too worried" about potential health effects from their exposure; one person, a driver, said he felt good and didn't have to drive tractors during several months of the year in the winter. The other person was not a driver and felt they were less exposed than drivers, and also cited the fact that they were not around tractors during winter months.

When asked how participants would use the results, three participants expressed that they would like to wear a mask after learning about the results. Two reported that masks are provided by their labor contractor employer, however many workers don't like to wear them and it is not part of the culture. One person said that they liked wearing masks and had been provided them by their employer, but they just get too hot to wear on many days.

> *"We don't like wearing masks, but I would wear one to reduce the risk."*

One participant mentioned that it can be hard to distance oneself from tractors during harvest in vineyard rows because people need to walk on one side of the row near the tractor while picking grapes. Another expressed that tractors should drive 2-3 rows away from working crews so that people are protected from not only diesel exhaust inhalation, but also from flying debris or other potential injuries from the large machinery. The other two participants said that they could use this information by distancing from the tractor, turning the tractor off, or wearing a mask. These two participants said that they were already distancing themselves from the tractor or turning the tractor off whenever possible prior to receiving these recommendations in the report-back materials. After the first round of report-back usability testing, the updated report-back formatting reflected improved understandability and accessibility of the content, but it did not necessarily affect participants' sentiments about usability or actionability of the information. This may be because there was a high degree of usability and actionability of the exposure reduction strategies in the report-back materials that were understood in the first round of interviews.

5.3.5 Summary of Report-Back Usability-Testing

Regardless of their own personal plans to use the information or take action, all eight participants responded that they thought the listed exposure reduction strategies would be realistic to be implemented by farmworkers and farmers in general. Six participants (75%) expressed a responsibility among farmers/employers to help protect farmworkers from diesel exhaust, including training and educating farmworkers, regular maintenance of tractors, and providing personal protective equipment like face masks. One person said that he thought employers should help their employees, but wasn't sure how exactly; he cited ideas of putting filters on tractor tailpipes, or moving the tailpipe or replacing the tractors as was mentioned in the report-back document. Three of these participants expressed that diesel exhaust exposure information and health risks should be shared with farmworkers broadly to increase awareness. Another participant said that they believed it was the responsibility of farmworkers themselves to consider this information and to take action reduce their exposure or not.

"Tienes que cuidarse a su mismo."

"You have to take care of yourself"

All eight participants expressed a desire for greater awareness of diesel exhaust exposure among farmworker communities so that farmworkers could prevent health risks. One person even suggested an agricultural event where researchers could share this information with other farmers and growers to get the word out. When asked about their perspectives on a need for government action to protect farmworkers, participants did not believe that that would be helpful. One person expressed that government agencies engage in long-term processes before changes occur, yet companies and individual farmers could take action more quickly. Another participant expressed that there are a lot of programs that already exist to help farmworkers.

All eight participants in the report-back usability-testing interviews expressed that this information was helpful to them and good to know. All interviews were conducted one-on-one with the participant interviewed by the researcher, though one participant happened to have their adult daughter with them during the interview, who helped to interpret the graphs. During the interviews, participants were asked how they would get more information if they had doubts or questions about their results return document after receiving it in the mail. When asked if they would call the number on the report-back document if they had questions or doubts after receiving their results return document, all 8 participants responded that they would. People also mentioned hypothetically talking to their employer about the results or searching for information online if they had questions.

Usability-testing interviews served as an opportunity to increase awareness and knowledge about diesel exhaust among the eight people that participated. Before receiving report-back information, seven out of the eight people that participated in usability-testing interviews were previously aware of diesel exhaust, either by simply noticing it through sight or smell, or more proactively trying to reduce their exposure to it. Five of these people reported their attitudes during work interviews, and among the three people that had not been previously interviewed due to logistical challenges, two of them reported previous awareness of diesel exhaust during the report-back usability testing. During previous work interviews, five out of the eight participants expressed no concern about diesel exhaust exposure, and two participants reported being somewhat concerned. Among the employees that had some previous awareness, but were not concerned, their level of awareness of diesel exhaust, knowledge of exposure prevention measures, and concern about long-term health effects related to exposure to themselves or other farmworkers increased after the report-back usability-testing.

There was only one employee who reported previous awareness and did not report increased awareness after discussing the report-back. Another employee did not express previous awareness or concern, but expressed concern about diesel exhaust after the report-back usability-testing interview. Seven participants (88%) reported mild to moderate concern about health effects among themselves or other farmworkers related to long-term exposure to diesel exhaust during usability-testing interviews. Participants also expressed knowledge they gained from the report-back materials related to preventing exposure and other sources of air pollution.

5.4 Discussion

These results highlight how report-back can increase EHL and advance exposure reduction efforts among farmworkers and farmers. Most participants wanted to receive their personal exposure results. This information is consistent with other studies, demonstrating that participants of environmental health studies want access to their results.[37] Participants were motivated to learn how much diesel exhaust they were exposed to (45%) and whether the exposure could affect their health (30%). Given that participants have a right to know about their personal exposure results, researchers have a responsibility to thoughtfully return results that are meaningful and appropriate for the study population.[131] All eight participants of report-back usability testing expressed gratitude for the information presented in the report-back materials.

Diesel exhaust is composed of many chemicals and working with tractors presents an inhalation risk for farmworkers, yet about half of farmworkers interviewed were not previously aware of this exposure risk. Awareness was expressed equally among farmworkers who drove tractors and those who did not. Conversely, concern about exposure was expressed only among tractor drivers. This may be due to the increased frequency of their exposure compared to other farmworkers who are not next to the tractor every day. Concern about exposure was thus driven by frequency and duration of exposure. A study of farmers in Iowa who drove diesel-powered tractors every day had an increased risk of lung cancer.[147] Given that diesel exhaust is ubiquitous across farms and is associated with a variety of serious health effects, such as cancer, stroke, heart attack, and respiratory, immune and metabolic diseases, more awareness among farmworkers is warranted.

Many participants also expressed a responsibility among farmers and employers to help protect farmworkers from diesel exhaust, including training and educating farmworkers, regular maintenance of tractors, and providing personal protective equipment like face masks. Our finding that farmworkers want more information about diesel exhaust and how to protect themselves, which was also found in a study of worker perspectives of diesel exhaust exposure in Canada.[128] This investigation emphasizes an opportunity for employers and farmworker advocacy organizations to share diesel exhaust education among farmworker populations to increase awareness. Employers participating in this study were largely unaware of support programs to provide funding to purchase cleaner-burning tractors with newer engines. After reporting back to farmers about study results, most farmers elected not to take advantage of programs that provide 50% to 100% of the cost of a new tractor because of the administrative burden required to apply for this funding, including providing 2 years of equipment maintenance, usage, and insurance records, proof of ownership, a dated and itemized quote for a new tractor with CARB-approved emissions reductions technologies, the requirement of destroying the existing tractor being replaced, and other requirements, which may vary slightly by air district.[137] The California Occupational Safety and Health Act's Hazard Communication Standard requires employers to notify employees of chemicals that cause cancer or reproductive harm in the workplace as per the Proposition 65 list of chemicals.[129] Diesel exhaust is a listed as a cancer-causing chemical on the Proposition 65 list, and employers must warn employees about the health risks. Many small to medium-sized employers, however, are unaware of this requirement.

Fifteen percent of participants interviewed expressed gratitude that they worked on organic farms and did not have to work with chemicals. Another participant who was not officially interviewed due to scheduling difficulties referenced the many chemical exposures that he experienced when working in Mexico in the past and appreciated not working with them in California. Although many people may not consider diesel exhaust as a chemical exposure, it contains thousands of airborne chemicals, some of which are associated with cancer and other adverse health outcomes. Our goal in the report-back process was to provide farmworkers and farmers with education about the health risks and exposure reduction opportunities related to diesel exhaust on their farms.

Report-back plays an important role in empowering study participants with data democratization and environmental health literacy.[34] Effective report-back strategies that participants found helpful in this investigation included: using graphics/images to display information; color schemes that denote information; minimal text that is appropriate for the audience; comparing individual results to the study population and other relevant comparisons from other studies; and including exposure reduction strategies at both the individual- and employer-level. Although more work is needed to standardize and document report-back methods, this investigation adds to our understanding of attitudes of exposure and report-back in the underexamined and vulnerable population of farmworkers. We have shared our report-back materials in the supplemental information to contribute to a shared report-back infrastructure among environmental health researchers. Report-back is not a one-size-fits-all approach due to the differences between studies and study populations; however, a streamlined approach where researchers have access best-practices, cost-effective tools, and resources to support their report-back will benefit researchers and study participants alike.[196] Report-back usability testing is a time-intensive process that not all studies may be able to afford, however when report-back is a consideration, building it into the initial study design and budgeting is recommended.[35,196]

There is still uncertainty among researchers about the best methods for reporting study results to vulnerable populations, for example participants in low-resourced settings with little ability to protect themselves from exposures, which may include occupational cohorts.[198] Reported concern about diesel exhaust exposure increased after usability-testing; however, participants were not alarmed, but rather seemed to be cautious given that they learned more information about diesel exhaust, the health effects of long-term exposure, as well as other sources of exposure to air pollution. Report-back studies have documented that concern among participants related to exposure results can lead to motivation to reduce exposure and or other types of action when exposure results are returned with relevant exposure reduction strategies.[215] Providing exposure reduction methods has been supported by study participants and researchers alike, and can lead to empowerment and increased EHL rather than helplessness.[131,214] Study participants have also reported that they would like their personal exposure results even if there is concern or uncertainty around health risk.[37,219]

The degree to which participants felt concerned may also be influenced by prior awareness of the exposure and the ability to mitigate one's exposure. For example, two participants expressed a prior awareness of diesel exhaust exposure and working in a way that would create more distance from the tractor tailpipe or using personal protective equipment to reduce their exposure. These examples of individual-level actions reflect control over their own ability to protect themselves. Participants also expressed increased concern about health risks that might be associated with long-term exposure over many years. Concern arising from uncertainty or low control in how long a work-related exposure will continue is consistent with the Job Demand-Control Model, and could also be related to job precarity or little control over employment trajectory.

Similarly, having some amount of control over one's job tasks or exposures can buffer the negative impacts of high job demand.[112] Many participants (75%) expressed intuitive ideas about reducing their exposure, including distancing oneself from the tractor (or specifically the tailpipe), or spending less time around a running tractor when possible. In the prepared report-back materials, we recommended exposure reduction strategies based on the hierarchy of controls; this framework seeks to control occupational hazards in order of the most effective, high-level actions to reduce exposures for many, to the least effective individual-level actions.[130] All eight participants interviewed in report-back usability testing said they believed these exposure reduction strategies would be helpful and realistic for farmworkers and farmers to implement.

It has been reported elsewhere, and is also congruent with our findings, that involving study participants in the design of report-back materials increases the probability of understandability, accessibility and usability of report-back materials among participants.[207,209,210] This is particularly important for populations with low levels of formal education or literacy. Involving study participants in the design of report-back materials also aids in building trust and engagement between researchers and participants.[41,42] There are many reasons why underserved or disadvantaged populations, such as farmworkers, may distrust researchers or government agencies due to historical and current power imbalances and injustices in the healthcare sector.[43] Report-back is a tool for not only translating science to affected communities and broader audiences and empowering them with increased science literacy, but also for building engagement and trust in scientific research. As described by Quandt et al., "knowing that the findings will be returned to the community in a timely manner and in terms that can be understood and provide the basis for community action will increase the willingness of communities to be involved in the research process."[209]

To our knowledge, outside of the internet-based DERBI platform, report-back methods with specific use of a video have not been published. Findings of this study indicate that all participants of report-back usability testing benefited from the video, reporting that they understood concepts from the report-back document more with more ease and confidence after watching the video. Participants interviewed in the PERE Study expressed that they found it helpful for research staff to talk with them about their report-back information and help them interpret it; among those interviewed who were not able to speak with a researcher, many participants expressed that they would have liked to.[37] Although a video does not replace research staff, with whom a participant can ask questions and engage in rich dialogue, a video represents a cost-effective way for researchers to help participants interpret their findings. Producing one video for the study population can help participants interpret their individual report-back results. The use of a report-back video is also particularly well-positioned for study populations with relatively low educational attainment, such as farmworkers.

Given the unique characteristics of this study population as mentioned above, some aspects of our findings on understandability, accessibility, and usability may not be generalizable to other farmworker populations. Other report-back studies have may similarly lack generalizability to other study populations given the unique study population characteristics and the personal aspect of report-back messaging and exposure reduction strategies.[207] The majority of participants wanting their results points to the interest and engagement of this study population. Additionally, farmworkers who consented to participating in work interviews and report-back usability-testing interviews may have been more engaged than participants who did not participate in interviews. Interviews were not intended to be representative of all farmworkers, but to explore attitudes about exposure and work conditions in this study population to provide context for the personal exposure monitoring interpretation and report-back development.

Report-back usability testing among eight participants may not reflect all study participants' views, but provides in-depth feedback from these eight people within the study population. Our report-back usability testing interviews may also be subject to the Hawthorne effect, in which study participants are aware that they are being observed and thus change their behavior.[154] This may have biased our results by indicating more positive feelings about report-back if there were a desire to demonstrate understanding or please the researcher in one-on-one interviews. Nevertheless, this information adds to the limited body of work describing diesel exhaust exposure experiences among workers and report-back of exposure results to farmworkers. Our findings and the findings of other report-back evaluations demonstrate the utility of participant-informed and participant-evaluated report-back. Report-back evaluation also creates dialogue between researchers and participants; it may build trust and engagement in research and break down knowledge hierarchies.

5.5 Conclusion

Most study participants (89%) wanted to receive their personal exposure results, and were motivated to learn how much diesel exhaust they were exposed to and whether the exposure could affect their health. Effective report-back strategies that participants found helpful in this investigation included: using graphics/images to display information; color schemes that denote information; minimal text that is appropriate for the audience; comparing individual results to the study population and other relevant comparisons from other studies; and including exposure reduction strategies at both the individual- and employer-level. All participants of report-back usability testing benefited from the video, reporting that they understood concepts from the report-back document more with more ease and confidence after watching the video.
Prior to report-back usability testing, half of farmworkers interviewed reported prior awareness of diesel exhaust, and 40% of them were specifically concerned about exposure for health reasons, particularly long-term exposure. The other half of interviewed farmworkers reported not thinking about diesel exhaust before. Many participants also expressed a responsibility among farmers and employers to help protect farmworkers from diesel exhaust, including training and educating farmworkers, regular maintenance of tractors, and providing personal

protective equipment like face masks. Our findings demonstrate that farmworkers lack awareness about diesel exhaust as an occupational exposure and that training is warranted.

Chapter 6. Conclusions about Exposure Reduction and Environmental Health Literacy

This dissertation aimed to understand sources of exposure and opportunities for exposure reduction in impacted populations in Northern California. While communities in the San Joaquin Valley of California have historically experienced poor air quality due to the valley's topography, they also experience disproportionate rates of poverty, asthma and cardiovascular disease compared to the rest of the state.[3,26,28,29] Farmworkers also experience disproportionate rates of depression, anxiety, obesity, diabetes, as well as occupational exposure risks of pesticides, heat stress, musculoskeletal stress and injuries.[30,33] Farmworkers face unique social and psychological stressors related to job security, immigration status, poverty, and inequitable access to resources.[31,32,33] Exposure to polycyclic aromatic hydrocarbons, black carbon, and nitrogen dioxide can result in adverse health outcomes to the respiratory, cardiovascular, and immune systems, as well as evidence of cancer and metabolic disease.[9,145,220] Characterizing these air pollutant exposure concentrations in these contexts is beneficial to understand methods of exposure reduction and identify future areas of research or interventions to ultimately advance health equity.

In Chapter 2, we examined the relationship between indoor and outdoor airborne PAH concentrations in residential settings, assessed the contribution of housing characteristics that affected this relationship, investigated how indoor household activities and product use affected indoor airborne PAH concentrations, and described the contribution of these indoor airborne PAH concentrations on urinary PAH metabolite concentrations. Measured airborne PAH concentrations were lower than previously measured values;[2] this confirms what long-term findings in Fresno, CA demonstrated regarding decreased ambient PAH concentrations in the last 20 years likely resulting from air quality regulations from the California Air Resources Board (CARB). As reported elsewhere, seasonal effects were also observed, with higher sample concentrations collected in the colder spring months than warmers summer and fall months.[2] We found evidence of infiltration of outdoor concentrations into home environments, which may have been facilitated by opening windows and home type. Frequently opening windows significantly increased infiltration of two outdoor PAH compounds (naphthalene (NAP) and fluorene (FLU)). Traffic volume and regularly using the attached garage were significant predictors of increased FLU concentrations. We also identified sources of indoor PAH exposure including burning candles, using gas-powered heat, and smoking or vaping in the home. Our results show some evidence that urinary metabolites are higher among active smokers versus participants exposed to second-hand or third-hand smoke. We found no association between air concentrations and urinary metabolites, suggesting that other sources of PAHs contribute to urinary metabolite concentrations, and more research is needed to understand the various drivers of urinary metabolite concentrations. PAHs are not commonly measured in the gaseous- and particle-phase due to complex field measurement techniques, and this work fills a gap in our understanding of residential exposure to these four PAH compounds.

In Chapter 3, we described methods from the Agricultural Off-Road Diesel Exposure (ACRE) Pilot Study and results from participant interviews. In this pilot study, we measured previously uncharacterized exposures to diesel exhaust among farmworkers and interviewed participating farmworkers about work practices and attitudes of report-back. Farmworkers were interviewed during personal exposure monitoring for diesel exhaust during typical full-shift farm work. They generally expressed satisfaction with their employment, reporting low to medium work stress (95%) and a high degree of perceived job stability (60%). This worker population, in agricultural operations where employers consented to researchers coming on site, were likely in more stable jobs than many farmworkers in this country.[106,107] Still, major contributors to stressful working conditions among those interviewed included high job demand (pressure for high productivity), long commute or work hours, and financial stress. Thirty-five percent of participants expressed feeling a sense of financial stress related to having smaller pay checks because of reduced work hours during hot temperatures, indicating economic precarity. Even among employees with generally supportive employers, most participants (80%) reported having to work in bad weather, including heat, rain, or wildfire smoke, expressing a sentiment that this is to be expected with agricultural work. This information confirms what has been reported about farmworker's economic precarity elsewhere and indicates an opportunity to support both farmworkers and small farmers.[134] This chapter sets the stage with contextual information about participants of this pilot study.

In Chapter 4, we reported our findings from personal exposure assessments among farmworkers to constituents of diesel exhaust. Our findings indicate that farmworkers are more highly exposed to black carbon (BC) in diesel exhaust than the general public and farmers. Task, tractor age (Tier), tractor cab style and tailpipe location were the primary factors impacting exposure concentrations. Driving diesel-powered tractors was associated the highest exposures in this study, however walking near or behind tractors to plant or harvest was also associated with some elevated exposures for PAHs. Tasks involving older tractors and closed cab and low tailpipe tractors in this study were associated with higher concentrations of BC, PAHs and nitrogen dioxide. Diesel exhaust is a known carcinogen and exposures should be reduced as much as possible. This pilot investigation identified opportunities for diesel exhaust exposure reduction among farmworkers and barriers to utilizing the equipment-replacement grants among farmers.

Lastly, Chapter 5 describes the development of worker-informed report-back materials and usability-testing interviews to evaluate them. Most study participants (89%) wanted to receive their personal exposure results, and were motivated to learn how much diesel exhaust they were exposed to and whether the exposure could affect their health. Effective report-back strategies that participants found helpful in this investigation included: using graphics/images to display information; color schemes that denote information; minimal text and accessible language for the audience; comparing individual results to the study population and other relevant comparisons from other studies; and including exposure reduction strategies at both the individual- and employer-level. All participants of report-back usability testing benefited from the video; they reported that they understood concepts from the report-back document more with more ease and confidence after watching the video. Prior to report-back usability testing, half of farmworkers interviewed reported prior awareness of diesel exhaust, and 40% of them were specifically concerned about exposure for health reasons, particularly long-term exposure. The other half of interviewed farmworkers reported not thinking about diesel exhaust before. Many participants also expressed a responsibility among farmers and employers to help protect farmworkers from diesel exhaust, including training and educating farmworkers, regularly maintaining tractors, and providing personal protective equipment like face masks. Our findings demonstrate that farmworkers lack awareness about diesel exhaust as an occupational exposure and that training is warranted.

This pilot study identified opportunities for exposure reduction among farmworkers, barriers to utilizing equipment-replacement grants among farmers, and effective methods of occupational exposure report-back among farmworkers. Farm work is an honorable occupation which feeds local communities in addition to bolstering the economy through national and international produce sales. Although farmworkers in this study expressed general satisfaction about their work conditions, many farmworkers experience high rates of health disparities, resource insecurity, as well as work-related exposures.[30,33] Compounding environmental and socioeconomic factors contribute to the burden of health disparities in marginalized communities.[221] Investing in farmworkers' health is essential and may require larger social safety net programs for farmworkers or additional support for small- and medium-sized farmers to remove economic incentives to work during extreme weather events. The federal Occupational Safety and Health Administration issued a Hazard Alert related to adverse health effects of diesel exhaust exposure in 2013; however, they have not developed a PEL nor a way to regulate diesel exhaust exposure outside of mining industries. More educational materials about diesel exhaust for employers in agriculture as well as other industries with high usage of off-road diesel-powered equipment is warranted. Although many employers are not aware, it is a requirement in California that workers are notified about carcinogens in their work environment such as diesel exhaust.

Results from this dissertation may inform the work of stakeholders and future research on air pollution exposures in impacted populations. Interventions related to weatherization of homes, use of portable air purifying devices, and education about indoor air quality could stem from this work to ascertain additional information about reducing residential exposures to air pollutants like PAHs. More research is needed to understand the various drivers of urinary metabolite concentrations given that we did not find an association between air pollutant concentrations and urinary metabolite concentrations; research during seasons and occasions of high PAH air pollution (e.g., winter, during wildfires) would assist in evaluations of potential associations. Once consideration that stems from this work is the importance of collecting personal air exposure measurements rather than area measurements in the home, when comparing them to urinary metabolite concentrations. Additionally, this pilot study identifies opportunities and barriers for agricultural employers and other stakeholders, including local and state government agencies and equipment manufacturers, to implement exposure reduction strategies, safety regulations, and a *Total Worker Health* approach. The National Institute of Occupational Safety and Health defines the *Total Worker Health* Approach as policies, programs and practices that integrate protection from work-related safety and health hazards with promotion of injury and illness-prevention efforts to advance worker well-being.[123] Implications from the ACRE pilot study include considerations among equipment manufacturers about placement of tractor tailpipes to reduce worker or driver exposure. Policy initiatives that could stem from this work include an educational campaign for agricultural employers and other industries with high usage of off-road diesel-powered tractors with information about training employees. This information may inform future epidemiological investigations among farmworkers by contributing to a job exposure matrix to characterize more holistically the cumulative exposures they experience at work. It may also inform research to evaluate the regional contribution to air pollution from agricultural equipment. Lastly, we hope the participant-informed report-back development, report-back usability-testing interviews, and report-back materials shared in this dissertation may be useful as researchers prepare report-back for future study populations, and particularly for farmworkers or other marginalized or disproportionately exposed populations. Our findings demonstrate that even among a study population experiencing occupational exposure, participants wanted their exposure results and appreciated report-back materials containing exposure reduction strategies.

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Appendices

Appendix to Chapter 2

Figure A1. Diagram of Harvard Impactor (left) for measuring PAHs and image of air sampling equipment set-up in participant homes (right)

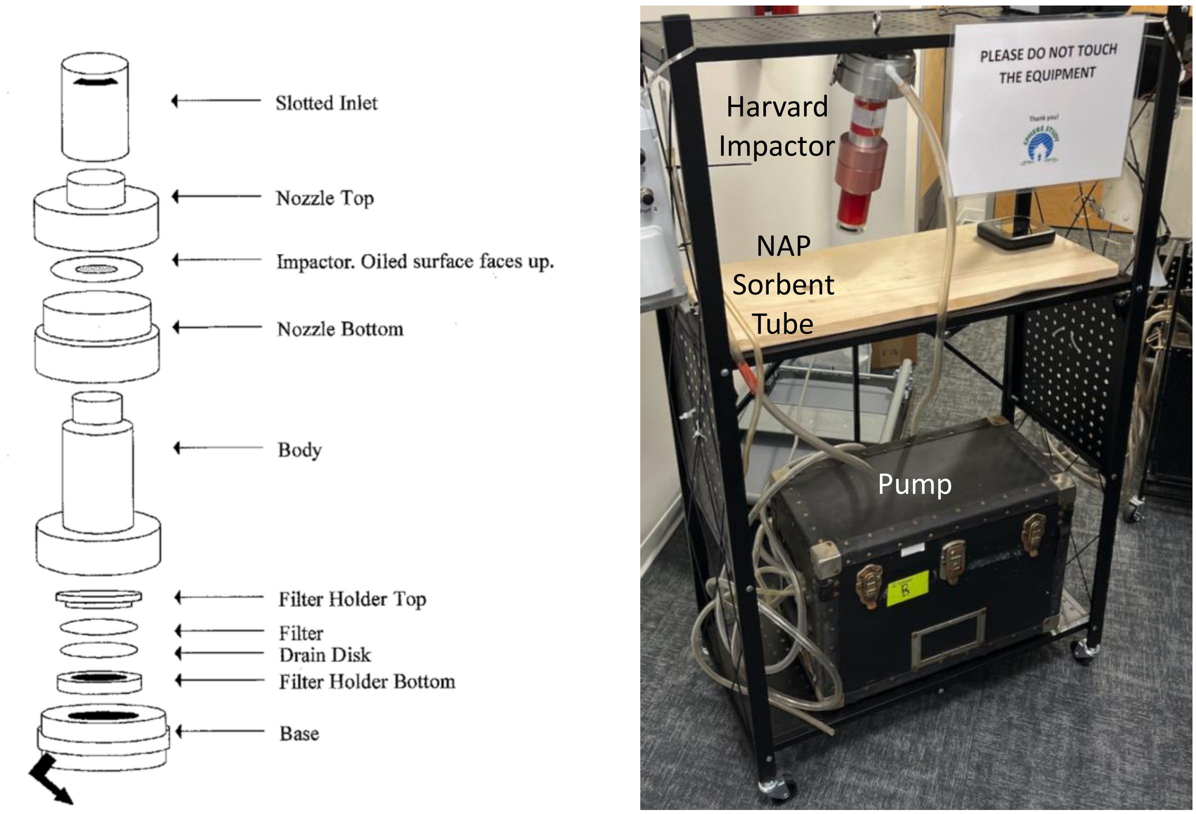


Figure A1. Diagram of Harvard Impactor (left) for measuring PAHs and image of air sampling equipment set-up in participant homes (right)

Figure A2. Equation for Specific Gravity Adjustment of PAH Urinary Metabolites

$$\boldsymbol{Concentration_{SG-adj}} = \boldsymbol{Concentration_{measured}} \times \frac{\mathbf{1.018 - 1}}{\boldsymbol{SG - 1}}$$

Table A1. Summary Statistics of Detected PAH Air Concentrations (ng/m^3) Coll
Indoors and Outdoors of Participating Homes

		Naphthalene (NAP) n=45	Fluorene (FLU) n=8	Phenanthrene (PHE) n=22	Pyrene (PYR) n=11
Indoors	Arithmetic Mean	69	4	9	6
	Standard Deviation	65	2	1	2
	Geometric Mean	45	4	9	6
	Geometric Standard Deviation	3	1	1	2
Outdoors	Arithmetic Mean	52	5	8	5
	Standard Deviation	58	2	1	2
	Geometric Mean	40	5	8	4
	Geometric Standard Deviation	2	1	1	2

Table A2. Results of Pearson's Correlation Tests on Logtransformed Indoor and Outdoor PAH Compounds

PAH Compound	Sample Size	Correlation Coefficient	95% Confidence Interval	p-value
NAP	104	0.61	(0.39, 0.76)	0.0000048
FLU	117	0.55	(0.32, 0.72)	0.000045
PHE	117	0.65	(0.45, 0.79)	0.00000044
PYR	66	0.28	(-0.12, 0.60)	0.16

Figure A3. Indoor Airborne NAP Concentrations and Urinary NAP Metabolites

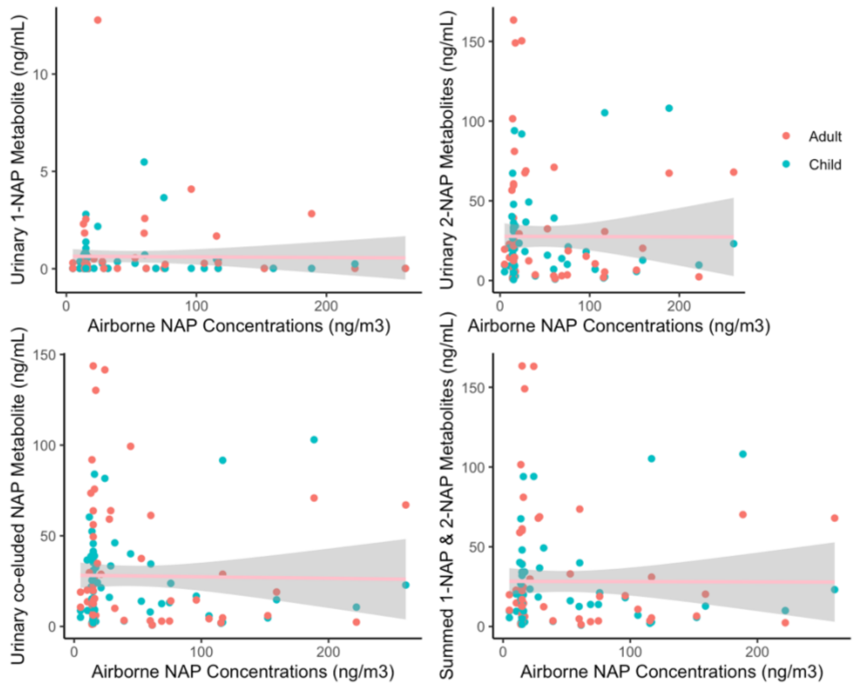


Figure A3. Pearson correlations of urinary PAH metabolite concentrations with indoor airborne PAH concentrations for adults and children

Appendix to Chapter 4

Figure B1: Equation for calculating Black Carbon mass concentration

$$BC_i = \frac{A_s}{Q \cdot E_{atn}} \times \frac{\Delta ATN_i}{\Delta t_i}$$

Figure B2. BC Concentrations Among Drivers Across all Farms on a log-transformed y-axis

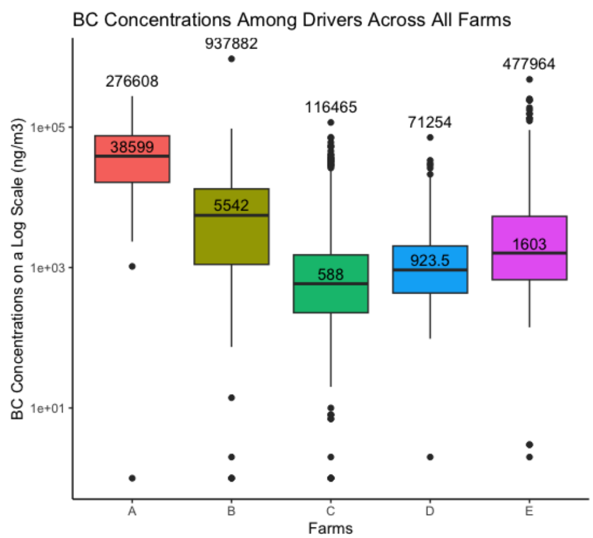


Figure B2. Log transformed black carbon concentrations are shown for all drivers across the five employers. Median values are noted in between the interquartile range on the plot and the maximum values are noted at the top of the distribution

Figure B3. Farm C Task Category Distributions as measured on an arithmetic y-axis and on a log-transformed y-axis

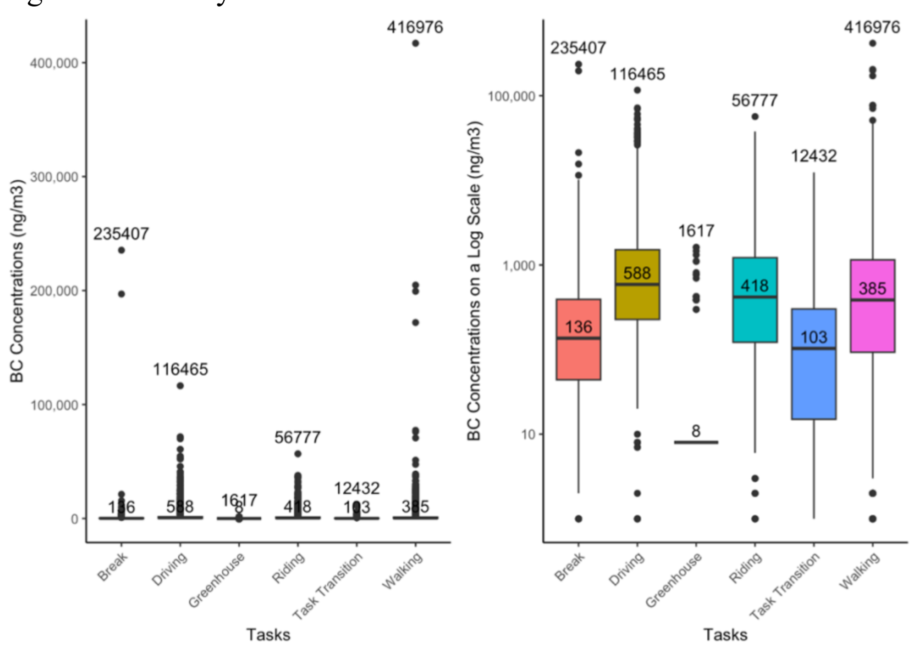


Figure B3. Farm C Task category distributions of black carbon on the arithmetic scale (left) and log scale (right) displayed in box plots. Median values are noted in between the interquartile range on the plot and the maximum values are noted at the top of the distribution

Table B1. Black Carbon Summary Statistics by Participant Work Shift

Sampling Month	Farm	Number of 1-minute concentrations collected during shift	Sample Duration (hours)	Arithmetic Mean (SD)	Max	25th Percentile	Median	75th Percentile	Geometric Mean (GSD)
April	A	129	2	43530 (50407)	276608	5657	26573	68128	15980 (6.84)
April	B	463	8	14571 (44385)	937882	3476	12012	17122	6376 (5.63)
April	B	508	8	9312 (8357)	94912	1434	10592	14254	4542 (5.61)
April	B	167	3	194 (251)	1470	16	160	322	93.6 (4.49)
April	B	510	9	2719 (3068)	18430	389	1484	4035	1279 (4.26)
April	C	436	7	874 (1634)	16278	128	256	832	344 (4.23)
June	C	327	5	720 (1610)	19185	61	208	666	228 (4.43)
July	C	335	6	1048 (1932)	16974	103	380	932	356 (4.86)
June	C	318	5	127 (341)	2600	6	29.5	38.5	20.4 (5.77)
August	C	300	5	3084 (12762)	99350	308	885	2008	781 (5.04)
August	C	343	6	2005 (4803)	36208	95	432	1235	434 (6.06)
July	C	101	2	2941 (7006)	37815	153	394	1105	850 (4.56)
July	C	96	2	3098 (10907)	77376	138	307	835	448 (4.43)
July	C	334	6	4949 (16106)	204757	502	1084	3569	1406 (4.43)
August	C	133	2	587 (1431)	9178	25	87	574	180 (6.72)
August	C	345	6	2663 (4245)	35644	497	1075	2990	1091 (4.69)
August	C	157	3	2004 (4050)	28589	132	368	1740	388 (9.80)
August	C	346	6	2886 (6508)	56777	172	652	2092	609 (6.53)
April	C	541	9	1594 (3362)	21726	197	653	1514	566 (4.44)
April	C	490	8	554 (1628)	24685	146	249	463	281 (2.60)
August	C	131	2	8842 (44665)	416976	782	1619	3328	1730 (3.53)
April	C	528	9	1823 (3655)	40782	308	636	1655	779 (3.41)
April	C	353	6	558 (1094)	13019	136	217	501	261 (3.80)
April	C	538	9	1253 (1796)	33080	375	766	1534	786 (2.60)
April	C	543	9	1703 (5218)	116465	386	864	2049	838 (3.42)
April	C	323	5	598 (1297)	10218	89	268	547	249 (3.52)
July	C	312	5	1766 (3811)	24911	170	411	1123	415 (5.48)

Table B1. Black Carbon Summary Statistics by Participant Work Shift

April	C	501	8	1969 (3168)	36613	374	1048	2131	759 (5.11)
April	C	335	6	3010 (7663)	71704	252	810	2335	884 (5.01)
April	C	429	7	400 (975)	12860	53	208	514	168 (4.48)
April	C	386	6	280 (957)	12432	24	59	162	72.3 (4.51)
June	C	336	6	1520 (3239)	32504	160	508	1413	528 (4.31)
July	C	386	6	3162 (7903)	69960	219	586	2018	858 (5.05)
April	C	434	7	1046 (1678)	12838	70	422	1293	318 (6.09)
April	C	393	7	603 (2097)	32836	68	170	469	182 (4.27)
April	C	258	4	290 (1042)	15365	53	95	221	119 (3.23)
April	C	429	7	217 (444)	4354	35	65	221	90.8 (4.10)
April	C	385	6	470 (1937)	24949	20	106	172	88.9 (4.53)
April	C	263	4	414 (721)	5548	82	256	413	194 (3.66)
April	C	284	5	114 (432)	3501	8	8	8	23.6 (6.50)
July	D	485	8	2144 (4663)	71254	594	996	1939	1083 (3.01)
July	D	447	7	1677 (3278)	40102	277	548	1783	696 (3.44)
September	E	285	5	10346 (24870)	240620	781	1908	8998	2439 (5.31)
September	E	318	5	8431 (33268)	477964	411	1354	4991	1530 (6.02)
September	E	151	3	8861 (26215)	240107	595	1694	7898	2286 (4.69)
September	E	265	4	2971 (11093)	155831	465	1149	2441	1029 (4.05)

Appendix to Chapter 5

Figure C1. Semi-Structured Interview Guide for Report-Back Usability Testing in English

Interviewer: Here, we're going to show you an example results template from this study. This is a prototype with hypothetical results, but pretend that this is your personal exposure results. Your feedback will help us design a clear, understandable, and usable results document for the farmworkers this study. You will get your individual results after we finalize the results document based on your feedback.

(We'd like feedback from you as though these were your personal results.)

We will ask you some questions to help us find out what information is clear, and how it could be clearer. I would appreciate you telling me what questions you have about this information.

Are you ready to continue?

Take a few moments to look at the results document,

1. Domain: Document Usability
   Question: For the statements below, do you strongly disagree, disagree, are neutral, agree, or strongly agree?

   I thought the document was easy to understand.

   I think I could use this document without the support of a scientist.

2. Domain: Document Understandability

   2.a. General Understandability
   Question: In this document, what do you find clear, and what do you find unclear?
   Probes:
   - Why is that clear or unclear?
   - What would help you to understand this clearly?
   - Which graphics/pictures are helpful in your understanding?
   - What text or language is helpful in your understanding?

   2.b. Graphics
   Question: Do you prefer the graphs with bars or the graphs with dots?
   Probes:
   - Why do you prefer these?

   2.c. Understanding Results

Question: Looking at Graph 2, can you explain to me how your results compare to other farmworkers' results?

3. Domain: Document Accessibility
   Question: Do you have all the information you need to understand your results or would you like more information?
   Probes:
   What additional information would be helpful for you to understand this?
   What aspects of the document are helpful and what is not helpful?
   How would you suggest that we improve the document?

Watch video.

4. Domain: Video Usability
   Question: For the statements below, do you strongly disagree, disagree, are neutral, agree, or strongly agree?

   I thought the video made the document easy to understand.

   I think I could use the video and document without the support of a scientist.

5. Domain: Video Understandability

   1.a. General Understandability
   Question: Did the video help you to understand the results document better?
   Probes:
   What was clear or unclear about the video? Why?

   What was helpful about the video?

   1.b. Graphics
   Question: After watching the video, do you prefer the graphs with bars or the graphs with dots? Why?

   1.c. Understanding Results
   Question: After watching the video, can you explain to me how your results compare to other farmworkers' results?

6. Domain: Accessibility
   Question: Do you have all the information you need to understand your results or would you like more information in the video?
   Probes:
   What additional information would be helpful for you to understand this?
   What aspects of the video are helpful and what is not helpful?
   How would you suggest that we change the video?

7. Domain: Usefulness
   Question: How will you use this information?
   Probes:
      How could you use this information?
      How could other farmworkers use this information?
      Might you share this information with anyone? If so, whom?
      Do you plan to do anything to reduce your exposure (breathe in less diesel exhaust)? If you, what do you plan to do? Why?

8. Domain: Attitude

   8.a. Question: How concerned are you about health effects from diesel exhaust? (Boronow et al., EDC)
      Very Concerned, concerned, somewhat concerned, slightly concerned, not at all concerned

      Probes:
      Do you think your attitude about diesel exhaust was influenced by participating in this study?
      Were you surprised by the results? What surprised you?
      How have your attitudes about diesel exhaust changed between before versus after you received your personal exposure results?

9. Domain: Exposure Prevention

   9.a. Question: Do you plan to do anything to reduce your exposure (breathe in less diesel exhaust)? Why or why not? What would you do?

   9.b. Question: What do you think you or other farmworkers could do to reduce your exposure to diesel exhaust (how much you breathe in)?

10. Domain: Community Action
    Question: What do you think could be or should done to protect farmworkers from diesel exhaust?
    Probes:
       What would you like to see at the community level?
       What would you like to see farmers/employers do or government do?
11. Domain: Getting Support
    Question: If you received this results document in the mail, and you didn’t understand something, would you call this phone number to talk to a researcher if you had questions?

    How else might you try to get the information you need?

12. Domain: Miscellaneous
    Question: Do you have any other questions for me?
    Probes:
        Are there any other resources that you'd like to know about?

Figure C2. Semi-Structured Interview Guide for Report-Back Usability Testing in English and Spanish

Entrevistadora: Ok voy a mostrarle un ejemplo de los resultados de este estudio pilóto. Este documento es un prototipo con resultados de otro trabajador agrícola, pero si le ayuda, puede imaginar que este documento tiene sus resultados de exposición. Busco comentarios y consejos para mejorar este documento para que se entiende bien, y esta claro y útil para otros trabajadores agrícolas. Cambiaré este documento según los comentarios y consejos y mandaré los resultados individuales a todos participantes/trabajadores agrícolas.

Le preguntaré algunas preguntas para entender mejor cuáles partes del documento sean claros, y cuáles no. Le agradecería que pudiera decirme todas sus preguntas sobre esta información.

Continuamos?

Tómese un momento para mirar el documento de resultados,

1. Tema: Usabilidad del Documento
   Pregunta: Con respecto a las siguientes afirmaciones, está usted: totalmente en desacuerdo (1), en desacuerdo (2), neutral (3), de acuerdo (4), o totalmente de acuerdo (5)?

   Me pareció que el document fue facíl de entender/comprender.

   Creo que yo podría usar este documento sin la ayuda de un científico.

   Imagino que la mayoría de la gente aprendería a usar este documento muy rápidamente.

   Me sentí seguro al entender este documento.

   Yo podría entender este document sin tener que aprender nueva información.

2. Tema: Comprehensibilidad del Documento

2.a. Pregunta: Con respecto del documento, qué le pareció claro y qué le pareció confuso?
Sondas:
- Porque le pareció claro o confuso?
- Qué le ayudaría a comprender esto con claridad?
- Quáles gráficos/imágenes le resultan útiles para comprender mejor la información?
- Quáles palabras/texto le resultan útiles para comprender mejor la información?

2.b. Pregunta: Prefiere usted los gráficos con barras o los gráficos con puntos?
Más:
- Porque?

2.c. Pregunta: Después de mirar Gráfico 2, me puede explicar como se comparan sus resultados con los de otros trabajadores agrícolas?

3. Tema: Accesibilidad del Documento
   Pregunta: Tiene toda la infomación que necesita para entender o comprender sus resultados o le gustaría más infomación?
   Sondas:
   - Qué información adicional le ayudaría?
   - Cuáles partes del document son útilies y cuáles no son útiles?
   - Cómo recomendaría usted que modificára el documento?

Ahora vamos a mirar el video, y luego tengo más preguntas.

4. Tema: Usabilidad del Video
   Pregunta: Con respecto a las siguientes afirmaciones, está usted totalmente en desacuerdo (1), en desacuerdo (2), neutral (3), de acuerdo (4), o totalmente de acuerdo (5)?

   Me pareció que el video facilitaba mi comprensíon del documento.

   Creo que yo podría usar este video y documento sin el apoyo de un cientíco.

   Me imagino que la mayoría de la gente aprendería a usar este documento muy rápidamente con el video.

   Me sentí seguro entender este documento con el video.

   Yo podría entender este video y documento sin tener que aprender nada nuevo.

5. Tema: Comprehensibilidad del Video

5.a. Pregunta: ¿El video le ayudó a comprender mejor el documento de resultados?
Sondas:
¿Qué estaba claro o no en el video? ¿Por qué?
¿Qué fue útil del video?

5.b. Pregunta: Después de ver el video, ¿prefiere usted los gráficos con barras o los gráficos con puntos? ¿Por qué?

5.c. Pregunta: Después de ver el video, ¿puede explicarme cómo se comparan sus resultados con los resultados de otros trabajadores agrícolas?

6. Tema: Accesibilidad
   Pregunta: ¿Tiene toda la información que necesita para comprender sus resultados o le gustaría obtener más información en el video?
   Sondas:
   ¿Qué información adicional sería útil para que entienda bien?
   ¿Qué aspectos del video son útiles y cuáles no?
   ¿Cómo recomendaría que modificara el video?

7. Tema: Utilidad
   Pregunta: ¿Cómo usará esta información?
   Sondas:
   ¿Cómo podría usar esta información?
   ¿Cómo podrían otros trabajadores agrícolas usar esta información?
   ¿Compartiría esta información con alguien? Y si, quien?
   ¿Planea hacer algo para reducir su exposición (respirar menos de los gases del escape diésel)? Y si, que planea o haría?

8. Tema: Actitud

   8.a. Pregunta: ¿Qué tan preocupado está por los efectos en la salud de los gases de escape de diésel? (Boronow et al., EDC)
   Muy preocupado (1), preocupado (2), algo preocupado (3), un poco preocupado (4), para nada preocupado (5)

   Sondas: ¿Cree que eso fue influenciado por el monitoreo del aire (su participación en este estudio)?
   ¿Le sorprendieron los resultados?
   ¿Cómo es diferente de lo que pensabas antes?

9. Tema: Prevención de la exposición

9.a. Pregunta: ¿Planea hacer algo para reducir su exposición (respirar menos gases de escape de diésel)?

9.b. Pregunta: ¿Qué cree que usted u otros trabajadores agrícolas podrían hacer para reducir su exposición a los gases de escape de diésel (cuánto inhala)?

10. Tema: Acción comunitaria
    Pregunta: ¿Qué cree que se podría o debería hacer para proteger a los trabajadores agrícolas de los gases de escape de diésel?
    Sondas:
        ¿Qué le gustaría ver a nivel comunitario?
        ¿Qué le gustaría que hicieran los agricultores/empleadores o el gobierno?

11. Tema: Obtener soporte
    Pregunta: Si recibiera este documento por correo y no entendiera algo, ¿llamarías a este número de teléfono si tuvieras preguntas?
    Sonda:
        ¿cómo obtendría la información que necesita?

12. Tema: Miscelánea
    Pregunta: ¿Tiene alguna otra pregunta para mí?
    Sonda:
        ¿Hay algún otro recurso que le gustaría conocer?

Figure C3. First Iteration of Report-Back Document in English

Air Monitoring Results for Participant A1

ACRE PILOT STUDY

Berkeley UNIVERSITY OF CALIFORNIA

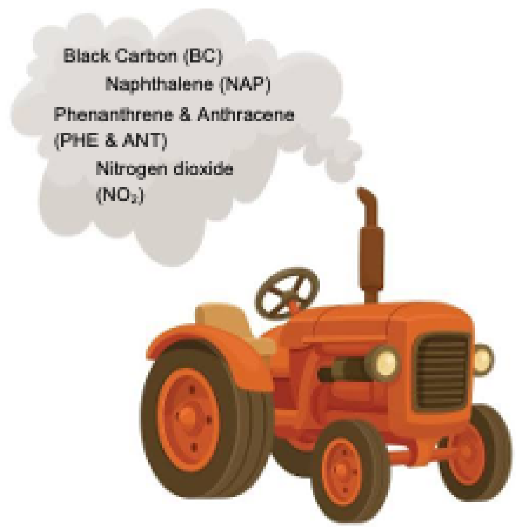
What did we measure?

- We measured four chemicals in the air that come from diesel exhaust while you worked in 2024.
- Black carbon (BC) is made up of very small particles in the air. Naphthalene (NAP), phenanthrene and anthracene (PHE+ANT) and nitrogen dioxide (NO_2) are gases.
- These air chemicals can also come from cars and trucks, cigarette smoke, burning wood, candles or incense, and some types of cooking, like grilling and barbequing.

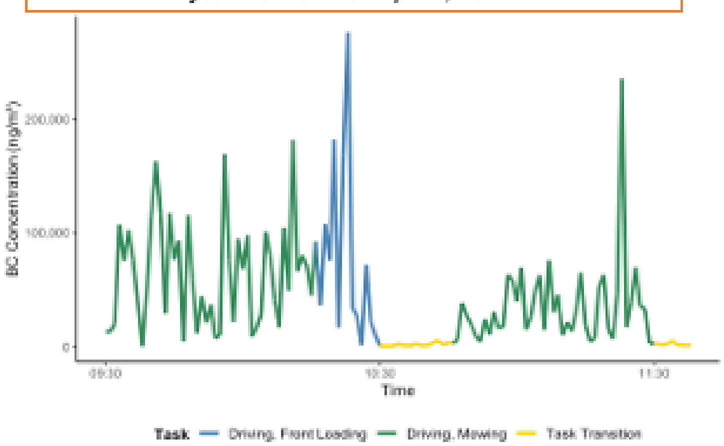
If you have any questions, please call or text us at (510) 810-8875.

Why did we measure diesel exhaust?

- Breathing in a lot of diesel exhaust is linked with harmful health problems like cancer, heart attack and stroke, worsening asthma, and harming the immune system.
- Before this study, there was no information about how much diesel exhaust farmworkers might breathe in at work.
- There are also many other chemicals in diesel exhaust that we did not measure in this study.



***Graph 1** shows your BC results collected every minute during your work shift on April 2, 2024.*



Summary of Your Results

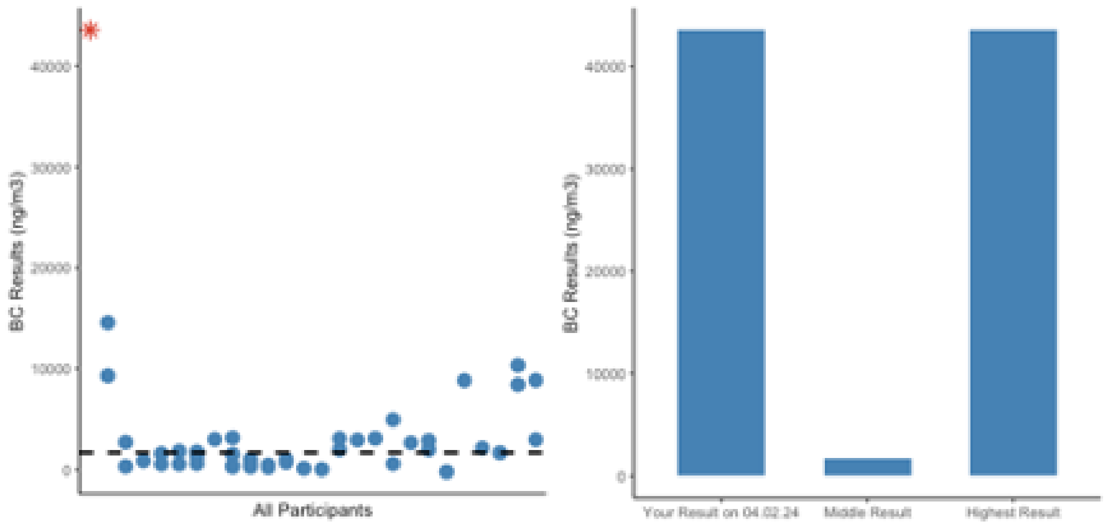
- Your BC result is higher than the middle point of the results. In other words, your result is in the top 50% of results from the study **(Graph 2).**
- Your NAP result is higher than the middle point of the results. In other words, your result is in the top 50% of results from the study **(Graph 3).**
- Your PHE+ANT result is higher than the middle point of the results. In other words, your result is in the top 50% of results from the study **(Graph 4).**
- Your ND result is higher than the middle point of the results. In other words, your result is in the top 50% of results from the study (There is no graph for NO_2).

1

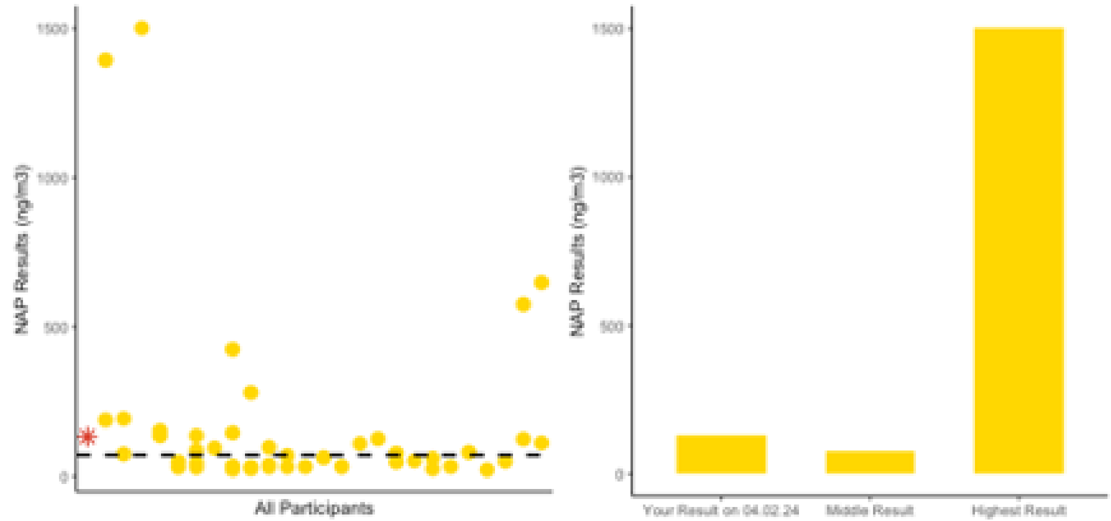
Graphs 2, 3 and 4 *show your results for three air chemicals compared to results of other farmworkers in the study. This result is an average from the total time you wore the vest each day.*

✳ = Your Result ● ● ● = Other Participants' Results — = Middle of Results

Graph 2: Black Carbon (BC) Results for You and This Study

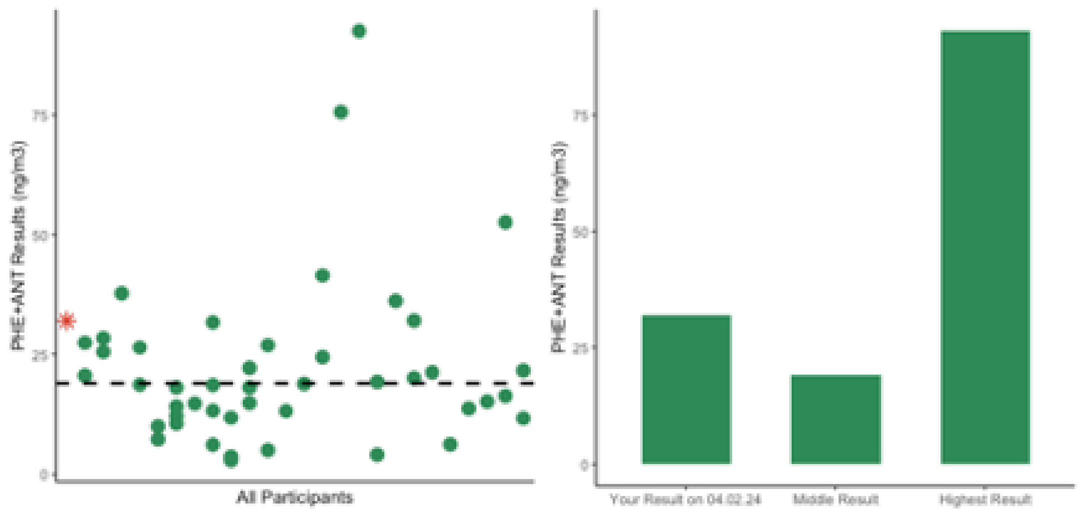


Graph 3: Naphthalene (NAP) Results for You and This Study



2

Graph 4: Phenanthrene and Anthracene (PHE+ANT) Results for You and This Study



Ways to Reduce Exposure:

- Take breaks away from running or idling tractors
- Turn off the engine instead of idling whenever possible
- Increase distance from the tailpipe of the tractor during walking tasks whenever possible
- Adapt the tailpipe location by a trained mechanic, if possible, to direct the diesel exhaust away from people
- Maintain the filter replacement schedule and the air ventilation system of closed cab tractors per manufacturer specifications
- Maintain tractor engines, such as regular oil changes and cleaning of diesel particulate filters
- Replace older tractors and equipment with newer ones or electric ones by applying for grants from local, state, and federal government agencies
- Fabric face coverings (like bandanas) do not protect people from diesel exhaust, but they may protect from dust. Filtering facepiece respirators (like N95 and KN95 certified by NIOSH) may be used to prevent exposure to diesel exhaust particles, but they are only effective if they fit the face well and create a seal.

Resources

- Diesel exhaust and health: https://ww2.arb.ca.gov/resources/overview-diesel-exhaust-and-health
- California Air Resources Board (CARB) grant programs to purchase newer tractors: https://ww2.arb.ca.gov/our-work/programs/farmer-program/how-apply-farmer-funding
- California Farmworker Foundation: https://californiafarmworkers.org/
- California Rural Legal Assistance Foundation: https://www.crlaf.org (559) 486-6278
- National Center for Farmworker Health, Inc.: https://www.ncfh.org/trainings/ (800) 377-9968
- Filtering Facepiece Respirators: https://www.cdc.gov/niosh/ppe/respirators/ffr.html
- California Workplace Hazard Helpline: (866) 282-5516

Figure C4. Second Iteration of Report-Back Document in English

ACRE PILOT STUDY

Air Monitoring Results for Participant A1

Berkeley UNIVERSITY OF CALIFORNIA

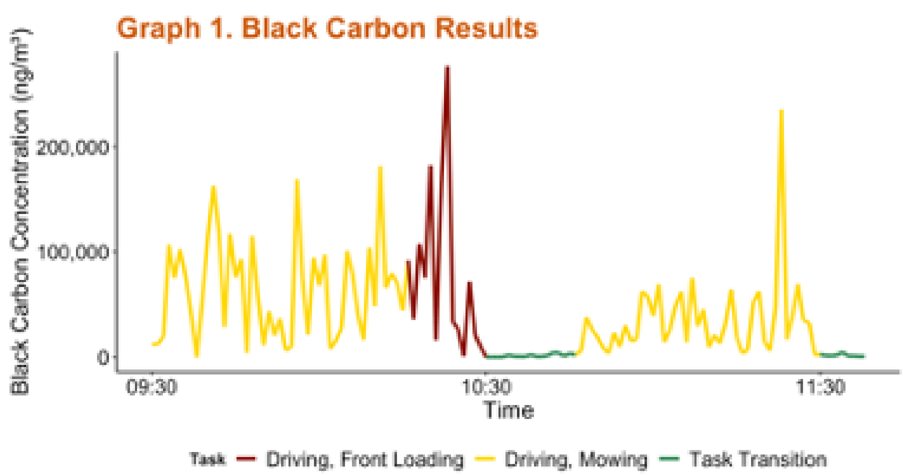
What did we measure?

- We measured four chemicals in the air that come from diesel exhaust while you worked in 2024.
- **Black carbon** is made up of very small particles in the air.
- **Naphthalene**, **phenanthrene and anthracene** are gases.
- These air chemicals can also come from cars and trucks, cigarette smoke, burning wood, candles or incense, and some types of cooking, like grilling and barbequing.
- There are also many other chemicals in diesel exhaust that we did not measure in this study.

If you have any questions, please contact Marley Zalay mzalay@berkeley.edu or (510) 810-8875.

Why did we measure diesel exhaust?

- Breathing in a lot of diesel exhaust is linked with harmful health problems like cancer, heart attack and stroke, worsening asthma, and harming the immune system.
- Before this study, there was no information about how much diesel exhaust farmworkers might breathe in at work.
- There are also many other chemicals in diesel exhaust that we did not measure in this study.



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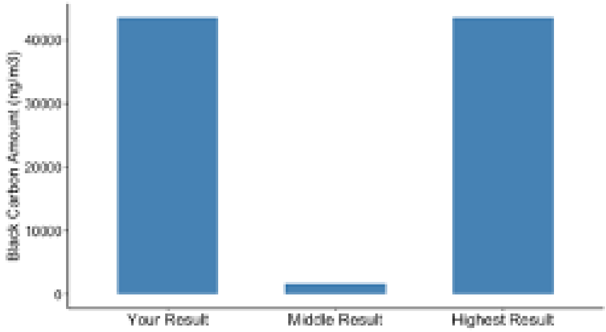
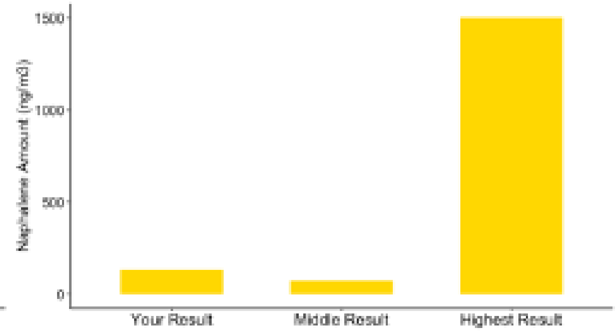
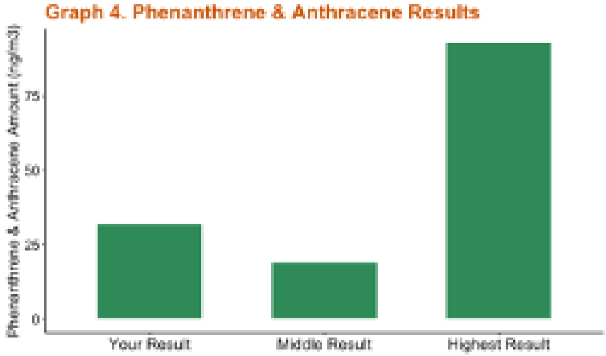
Graph 2. Black Carbon Results



Graph 3. Naphthalene Results



Graph 4. Phenanthrene & Anthracene Results



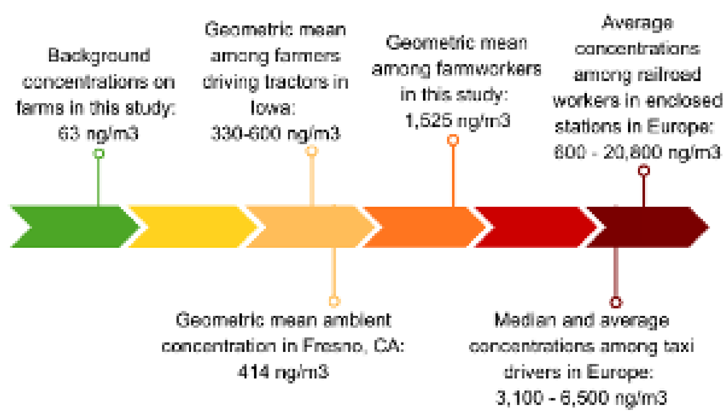
What did we find out in this study?

In this study, we found higher diesel exhaust results when:

- People were driving tractors
- Tractors were older
- Tractors has closed cabs and low tailpipes

Also, some people had high exposure to diesel exhaust during some breaks.

How do these results compare to other studies of black carbon?



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Ways to Reduce Exposure:

- Take breaks away from running or idling tractors
- Turn off the engine instead of idling whenever possible
- Increase distance from the tailpipe of the tractor during walking tasks whenever possible
- Adapt the tailpipe location by a trained mechanic, if possible, to direct the diesel exhaust away from people
- Maintain the filter replacement schedule and the air ventilation system of closed cab tractors per manufacturer specifications
- Maintain tractor engines, such as regular oil changes and cleaning of diesel particulate filters. Replace older tractors and equipment with newer ones or electric ones by applying for grants from local, state, and federal government agencies
- Fabric face coverings (like bandanas) do not protect people from diesel exhaust, but they may protect from dust. Filtering facepiece respirators (like N95 and KN95 certified by NIOSH) may be used to prevent exposure to diesel exhaust particles, but they are only effective if they fit the face well and create a seal.

Resources

- Diesel exhaust and health: https://ww2.arb.ca.gov/resources/overview-diesel-exhaust-and-health
- California Air Resources Board (CARB) grant programs to purchase newer tractors: https://ww2.arb.ca.gov/our-work/programs/farmer-program/how-apply-farmer-funding
- California Farmworker Foundation: https://californiafarmworkers.org/
- California Rural Legal Assistance Foundation: https://www.crlaf.org (559) 486-6278
- National Center for Farmworker Health, Inc.: https://www.ncfh.org/trainings/ (800) 377-9968
- Filtering Facepiece Respirators: https://www.cdc.gov/niosh/ppe/respirators/ffr.html
- California Workplace Hazard Helpline: (866) 282-5516