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Long-term analysis of the relationships between indoor and outdoor fine particulate pollution: A case study using research grade sensors

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HIGHLIGHTS
• Granular indoor/outdoor air quality research over long term periods is understudied.
• We used research grade sensors at three building locations to capture PM2.5 trends.
• A statistical comparison of indoor/outdoor pollution levels was performed.
• Inversions, wildfires, and fireworks have different building infiltration patterns.
• Indoor air quality is highly variable and strongly dependent on pollution events.

GRAPHICAL ABSTRACT

The growing concern of air quality and its associated health-related impacts has led to increased awareness of pollutant exposure. Most human populations spend the majority of their time indoors and the COVID-19 pandemic has likely exacerbated this behavior. While significant amounts of research have focused on outdoor air quality, to date there have been no studies that examined simultaneous long-term trends on indoor and outdoor air quality on a site using research-grade sensors. We measured fine particulate matter (PM2.5) for a year using sensors located on the rooftop, air handling room, and indoor office space in a building and captured the impacts of three types of regularly occurring elevated pollution events: wintertime atmospheric inversions, wildfires, and fireworks. The events had different magnitudes and durations, and infiltration rates varied for each event leading to dissimilar indoor air pollution levels. The building’s air handling unit and different environmental conditions (lower indoor humidity and temperature during the winter) combined to reduce indoor pollution from inversion events however, particulate matter from wildfires and fireworks infiltrated at higher rates. Together, this suggests possible intervention strategies, such as ventilation rates and filter upgrades, that could be used to mitigate contaminant intrusion during elevated pollution events. This year-long study illustrates an array of ways that elevated pollution events interact with the protective effects that buildings have against air pollution for its occupants. Furthermore, we show that outdoor air pollution is an important variable to consider when studying indoor air quality as contaminant infiltration is strongly dependent on the specific pollution source.

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1. Introduction

In the United States, more than 141 million people live in areas with unhealthy levels of air pollution, and pollutant exposure rates are more likely to be determined by race and socioeconomic status than any other factor (Bell and Ebisu, 2012; Clark et al., 2014). While most people are aware of the harms of air pollution, fewer people are aware that their indoor air quality may be worse than their outdoor air quality (Chen and Zhao, 2011). These findings are relevant because humans normally spend 80% or more of their time indoors (Jenkins et al., 1992), and as a result of the COVID-19 pandemic, many people will continue working from home into the future (Bick et al., 2020). As a result, indoor air quality is of growing importance. Prior studies in this area have contributed greatly to our understanding of air quality in an urban setting (Giani et al., 2020) and how the built environment interacts with pollution-specific events (Baek et al., 1997).

To contribute further to this body of work, we use a network of research grade fine particulate matter (PM$_{2.5}$) sensors placed both inside and outside a building to quantify emissions trends around this pollutant. A complete table of abbreviations used is found in Appendix A.

PM$_{2.5}$ is of significant interest because studies increasingly suggest that it contributes to a range of illnesses including asthma, chronic obstructive pulmonary disease (COPD), heart disease, pneumonia, depression, low birth weight, and increased mortality (Brauer, 2010; DeVries et al., 2017; Hackmann and Sjöberg, 2016; Liu et al., 2009; McCreanor et al., 2007; Pirozzi et al., 2018a; Pirozzi et al., 2018b). Children are especially susceptible to the health and developmental impacts of air pollution (Mendoza et al., 2020; Mullen et al., 2020) because of their unique biological vulnerabilities, age-related patterns of exposure, and lack of control over their own environmental circumstances as they may spend more time outside than adults (Landrigan et al., 2010). With increasing wildfire events (Abatzoglou and Williams, 2016; Malila et al., 2015), elevated PM$_{2.5}$, which was historically a wintertime phenomenon due to atmospheric inversions (Bares et al., 2018; Whiteman et al., 2014), is now also becoming a health concern during the warmer seasons. For these reasons, PM$_{2.5}$ is an important pollutant to study and understand for a range of stakeholders.

To best understand potential exposure trends for PM$_{2.5}$, we study the short- and long-term relationship between indoor and outdoor air quality in an urban building in Utah’s Salt Lake Valley (SLV). We capture three different types of elevated pollution events: winter inversion, seasonal wildfire, and local fireworks. Despite the common belief that being indoors will protect individuals from poor air quality, we find that indoor PM$_{2.5}$ concentrations vary greatly and are source specific. Indoor conditions may be just as harmful to human health, especially during volatile pollution episodes, which can be misleading because they are often shorter events. Such findings have serious implications for building air quality, urban planning, public health, air quality policy, and other related policies (e.g., school recess policies, warning or awareness programs for the young, elderly, or health vulnerable populations, etc.).

This study is novel for at least four reasons. First, this project used research grade PM$_{2.5}$ sensors for this study. While low-cost sensors can be helpful for improving air quality campaigns because of their differential response time (Bulot et al., 2020) and ability to track sources of pollution (Popoola et al., 2018), questions remain over the accuracy and reliability of the data they produce, especially if humidity and temperature variability are present and with complex emissions sources and concentration profiles (Bulot et al., 2020). It has become clear that low-cost sensors are no longer adequate and increasingly, research grade sensors are necessary at varied scales for improved data reliability and validity (Mead et al., 2013). The use of research grade sensors, therefore, has the potential to provide a far more complete assessment of the high-granularity air quality structure generally observed in the urban environment, and could ultimately be used for quantification of human exposure, air quality monitoring, public health, and legislative purposes.

Second, while studies of indoor (Tran et al., 2020) or outdoor air quality are common in the literature, due to data complexity issues, the cost of sensors, and the technical maintenance required to manage sensors, it is uncommon to find research that captures both types of ambient air quality simultaneously without using estimation methods. Instead, most work in this area (Giani et al., 2020; Ljungman et al., 2018; Tsai et al., 2019) uses various forms of estimation to measure air quality and while this approach can be used for overall daily exposure, it lacks detail about elevated pollution events, which are highly random. In fact, one major pollution event discovered in our data was a private event featuring fireworks. Such events, while potentially lethal to some vulnerable groups, would simply be missed by most major studies.

Third, this research uses sensor measurements to illustrate multiple regularly occurring pollution events, that are intense enough to rise above potential noise from other sources including anthropogenic emissions from the highly-trafficked roads and large emissions associated with commercial buildings, over a full year using direct measurements. Focused studies on single pollution events (Shen et al., 2020) have been foundational in establishing the importance of these elevated events on human health. Likewise, important advances in the field have come from research that attempts to study multiple pollution events over time, but this work has relied on satellite data (Ljungman et al., 2018) and pollution simulation techniques (Tsai et al., 2019), not real-time pollution measurements. To address this, we study and present detailed measurements of three types of elevated pollution events with the building as the unit of analysis to illustrate the importance of granularity and direct measurement in the study of air quality.

Fourth, this study is novel because it measures long-term air quality trends in fine temporal detail to understand what may be missed in estimation type studies. For instance, studies that focus on detailed snapshots (Apte et al., 2017) and short-term air quality impacts in detail (Sunyer et al., 2017) have been vital for illustrating the associations between daily variation in air pollution and a variety of effects. For instance, Sunyer et al. (Sunyer et al., 2017) show the association between daily traffic pollution and lower attention in children, suggesting that short term exposure to air pollution can have consequential impacts. Land use regression techniques have proved to be a fast and accurate means for estimating long term and daily emissions exposure in urban settings (Dons et al., 2014). However, these approaches, like estimation techniques (Lipfert et al., 2006) and classic dispersion calculation approaches (Clenc-v-Aas et al., 1999), lack the ability to model or capture short term major pollution events, which can be deadly because of their quick onset and severity. If only short-term or estimation approaches are used to study this phenomenon, the impact of pollution, which is generally small on a day-to-day basis, will be grossly underestimated. Instead, we must move beyond estimation to provide data that reflects real measurement of spatial and temporal variations.

To address these gaps in the literature, this research attempts to combine highly granular, long- and short-term air quality measurements using research grade sensors located at indoor and outdoor sites (e.g., inside the building, in the air handling room of the building, and on the outside) of the same building. Through this indoor/outdoor approach, we were able to analyze, in sharp detail, a variety of pollution events.

2. Methods

To study the relationship between indoor and outdoor ambient air, three research-grade, Met One Instruments ES-642 particulate sensors, with an inlet sharp cut cyclone used for selective measurement of PM$_{2.5}$ (Met One Instruments, 2013) were located at the Unified State Laboratories in Taylorsville, Utah (Fig. 1), an urban setting in the SLV. The study site is near three heavily trafficked roads, Bangerter Highway,
Interstate 215, and Redwood Road, as well as a community college and retail stores. A regulatory air quality sensor is located approximately 10 km northeast of the study site.

The Unified State Laboratory Building, Module 1, is an 82,000 square foot, three-story laboratory building including a Biosafety Level (BSL) 3 laboratory as well as support areas including some office space. The air supply and exhaust systems include two supply air handling units (AHUs), two general exhaust AHUs and five dedicated exhaust fans for the BSL 3 labs, perchloric acid exhaust and radioisotope exhaust. Further information on the building’s heating, ventilation, and air conditioning (HVAC) system is found in Appendix B. All three sensors for this project have a tolerance of 1 μg m⁻³ (Met One Instruments, 2013) and read data continuously at 10-s time intervals. The sensors were placed on the rooftop, in the air intake room, and within an internal office space. All three were installed on April 30, 2018 and were online until May 30, 2019. Since the study took a little over a year, no calibration was performed during the experiment time frame. The manufacturer states that factory calibration is generally necessary after 2 years of use and these sensors have been tested and found to robustly match reference sensors (Mendoza et al., 2019). The data was stored locally in a Raspberry Pi 3 computer that was directly connected to and read the data from the ES-642 sensor via a serial cable. The data was then downloaded from the Raspberry Pi 3 to a laptop for analysis using an ethernet cable. Data processing and analysis was done using R Version 3.6.3 software (R Core Team, 2019).

We aggregated the data to 1-min resolution, by using the arithmetic mean, and we established a reference baseline by averaging the ten lowest average pollution days, as measured by the rooftop sensor readings. In order to limit the influence of spurious data, we used the “Winsorize” function found in the DescTools R package (Signorell et al., 2016). Winsorizing a set of data involves limiting the range of data by replacing extreme values to a pre-determined maximum and minimum. For this study we set the default minimum value to the 5% quantile and maximum to the 95% quantile so any values outside that range were replaced to either the 5% or 95% quantile. We examined the impact of three types of elevated pollution events: wintertime inversions, wildfire episodes, and public/private fireworks events on sensor readings. Appendix A includes a complete timeline of critical pollution events captured through this project. We also compared the hourly air quality date from the regulatory sensor against the hourly-aggregated rooftop sensor data for the whole study period as well as for the elevated pollution events.

3. Results

3.1. Baseline weekday and weekend cycles

Table 1 and Fig. 2 show the results for weekday and weekend PM₂.⁵ values for the ten lowest pollution days based on the rooftop readings. The weekday diurnal cycle (Fig. 2.a) shows the impact of pollution from the two rush hour peaks (8-10 am and 6-8 pm). The weekend diurnal cycle (Fig. 2.b) shows elevated PM₂.⁵ early in the morning (midnight – 8 am) and late in the evening (8 pm – midnight), which could be attributed to social and recreational activities as the study location is near several well-visited sites including a shopping mall and community college. Elevated evening pollutant concentrations are also a result of a lower atmospheric
boundary layer due to the colder nighttime temperatures. While the rooftop and air handling room readings tracked relatively closely to each other (Fig. 2.c–d), the indoor sensor consistently reads between a quarter to half as high as the outdoor sensors. The mean daily concentration was approximately 1 μg/m³ for the rooftop and air handling room, and 0.5 μg/m³ for the office for both weekdays and weekends. In this research, we consistently used a linear statistical model to associate all PM2.5 relationships between different sensors as this method provided the best fit for the data. Related statistical values are also provided in Table 1.

### Table 1

| Event           | Indoor vs. rooftop readings | Air handling room vs. rooftop readings |
|-----------------|-----------------------------|---------------------------------------|
| Intercept       | Coefficient                 | R²                                    |
| Intercept       | Coefficient                 | R²                                    |
| Weekday         | 0.18385                     | 0.29152                               |
| (2e-16)***      | (2e-16)***                  | (2.2e-16)***                          |
| Weekday         | 0.14290                     | 0.41853                               |
| (2e-16)***      | (2e-16)***                  | (2.2e-16)***                          |
| Weekend         | 0.18385                     | 0.29152                               |
| (2e-16)***      | (2e-16)***                  | (2.2e-16)***                          |
| Weekday         | 0.28319 (4.3e-14)***        | 0.75171                               |
| (2e-16)***      | (2e-16)***                  | (2.2e-16)***                          |
| Weekday         | 0.3788                      | 1.53373                               |
| (2e-16)***      | (2e-16)***                  | (2.2e-16)***                          |

**Fig. 2.** Minute-resolved baseline weekday and weekend cycles using the ten lowest rooftop pollution days: a) Weekday and b) Weekend, and comparison between indoor and outdoor pollutant concentrations for: c) Weekday and d) Weekend.
3.2. Impact of wintertime inversions on air quality

Fig. 3a presents the impact of a typical persistent cold air pool, commonly known as a wintertime inversion, on air quality. The dashed horizontal lines represent air quality index (AQI) level cutoffs (United States Environmental Protection Agency, 2016). A gradual buildup had started a few days earlier (December 4th) with partial daily reductions, but on December 7th the pollutant levels stabilized above orange (“unhealthy for sensitive groups”) air quality. December 8th was the first day when the outdoor air quality reached red (“unhealthy”) levels outdoors and yellow (“moderate”) levels indoors. December 9th and 10th followed a similar pattern as December 8th however, PM$_{2.5}$ had begun to accumulate indoors because the levels stayed consistently above yellow while the outdoor sensors read orange. December 11th experienced a partial clearing out during the middle of the day and on December 12th there was a complete clear out due to a mild snow event. Although the indoor pollutant concentration is generally about one third as high as the outdoor pollutant concentration, there is a possibility that longer events could generate larger indoor pollutant buildups. In addition, the indoor air pollution readings often crossed into the yellow air quality level and were ten times greater than the baseline air day throughout the five-day pollution event. For this inversion event, the air handling room sensor was offline as there was maintenance taking place there at the time.

3.3. Impact of wildfire events on air quality

The summer of 2018 was characterized by a large number of wildfire episodes, particularly in the American West. While there were a few local wildfires, the majority of pollutants traveled from California, Oregon, and Washington State due to the prevailing westerly winds. During the period of August 23rd-24th, three wildfires were active in California: 1) Stone (Modoc County), 2) Mill Creek 1 (Humboldt County), and 3) Front (San Luis Obispo and Santa Barbara Counties). Fig. 3b displays the PM$_{2.5}$ patterns that occur with the confluence of these wildfire events. During this elevated pollution event, the concentration differences between the indoor and outdoor sensors were much smaller (approximately 10–15% less) than for referenced baseline days (Fig. 2) or inversion events (Fig. 3a), both of which show a difference of about 50%. For nearly 48 h, indoor air quality reached levels considered problematic for health compromised populations (orange) and nearly reached levels considered unsafe for all populations (red). Wildfire episodes are expected to increase in the upcoming decades (Schoennagel et al., 2017) and these results suggest that such events may need special policies (e.g., higher efficiency filters or lower intake of outside air) to better protect residents if buildings offer little air quality protection from wildfire events.

3.4. Impact of fireworks on air quality

3.4.1. 4th of July fireworks

Fig. 3c presents the impact of 4th of July fireworks on air quality by examining July 4th and July 5th, 2018. The vertical axis range on this figure is more than twice as large as the wildfire event (Fig. 3b) and more than three times larger than for the inversion days (Fig. 3a). The July 4th fireworks display started at 10 pm in Salt Lake County and the air quality effects are noticeable almost immediately. For approximately 3 h, the air quality remained red with a few spikes into purple (“very unhealthy”) levels. Spikes on the red line happen sporadically throughout the 2-day study period were likely fireworks released by individuals living nearby. During the most polluted hours (10 pm – 1 am), the indoor air quality reached orange air quality levels. It was only after 8 am on July 5th that indoor air quality returned to pre-fireworks levels. Since fireworks pollution is a combination of primary (smoke) and secondary particle material produced by additional chemical reactions, the effect on indoor air quality is due to a combination of both. As this pollution event illustrates, fireworks events are typically shorter than other types of pollution events, lasting only a few hours at most. However, even in this short period we found significantly elevated, and unhealthy, air quality levels both indoors and outdoors.

3.4.2. Private event fireworks

On August 17th, 2018 a private event released fireworks approximately 8 km from the USL site (Fig. 3d). The fireworks display started at 9 pm and lasted about 30 min. While its impact on air quality – in terms of both magnitude and duration of the accompanying increase in PM$_{2.5}$ levels – was markedly lower than the July 4th event (Fig. 3d), the indoor pollution levels still increased to orange for several minutes. Thus, the pattern was consistent with the other firework example, but reflected the smaller scale of this firework event.

3.5. Relationships between indoor and outdoor air quality

Table 2 and Fig. 4 show the relationship between indoor and outdoor air quality for the elevated pollution events. As illustrated in Table 2, the relative ratio of the indoor to outdoor readings are all statistically significant to the p < 0.001 level, with each elevated pollution event presenting a unique pattern. For instance, the slope of the coefficient for wildfires is more than double that of inversions. This suggests that indoor pollutant concentration is approximately 77% of rooftop air pollution, as evidenced by the coefficient in Table 2. This may suggest that wildfire related particulate matter is more easily able to avoid being filtered by building HVAC systems or is more chemically stable than inversion particulate matter. Thus, wildfires may warrant special warning systems for health vulnerable populations. The indoor air quality implications of the firework events closely resembles that of inversions in terms of the infiltration rate, however the absolute magnitude of pollution is markedly larger, albeit of shorter duration. These findings suggest that outdoor air pollution levels may be helpful when trying to predict or model indoor air quality because contaminant infiltration appears to be related to outdoor pollution sources or types. During the inversion event (Fig. 4a), the office pollutant concentration was approximately 29% of the outdoor concentration. On the other hand, the wildfire event (Fig. 4b) resulted in the office concentration being approximately 78% of the rooftop reading. The fireworks events (Fig. 4c–d) display a combination of the patterns from the inversion (Fig. 4a) and wildfire (Fig. 4b) events. The office sensor readings were similar to the rooftop readings until about 40 mg/m$^3$ when the office air pollution leveled off while the rooftop pollutant concentration continued to increase. This was likely a result of a combination of building filtration as well as the decay of secondary PM$_{2.5}$. During the wildfire (Fig. 4b) and fireworks events (Fig. 4c–d), the air handling and rooftop readings were nearly identical since little filtration takes place between the two locations.

3.6. Comparison against regulatory sensor data

The regulatory sensor data (Hawthorne) and USL rooftop sensor readings are shown in Table 3, Fig. 5, and Appendix C Figures C.1 and C.2. While the full time series showed the closest correlation, the elevated pollution events resulted in relatively similar patterns. It must be noted that the two sensors are located nearly 10 km apart and in different urban typologies, with the USL sensor surrounded by more industrial and commercial buildings, whereas the Hawthorne sensor is in a residential neighborhood. Furthermore, events such as fireworks are

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2 The 24-h average AQI breakpoints along with the respective index colors are (in $\mu$g/m$^3$): 0.0–12.0, “Good” (green); 12.1–35.4, “Moderate” (yellow); 35.5–55.4, “Unhealthy for sensitive groups” (orange); 55.5–150.4, “Unhealthy” (red); 150.5–250.4, “Very Unhealthy” (purple); 250+,”Hazardous” (maroon).
Fig. 3. Minute-resolved impact of elevated pollution events on air quality: a) December 7th-12th inversion, b) August 23rd-24th wildfire, c) 4th of July fireworks, and d) Private fireworks event on August 17th. The red, blue, and black lines correspond to the rooftop, air handling room, and office sensors, respectively. The horizontal lines correspond to AQI levels. The vertical scales are different for each event.
strongly localized and factors such as tree cover and land use can impact air quality (Mendoza, 2020) resulting in marked differences between air quality readings taken at different sites within the same urban area. Despite these factors, the close association between the USL and Hawthorne readings (Appendix C) provide confirmation that the USL sensor data are representative of the ambient air pollution.

### 4. Discussion and conclusions

#### 4.1. Discussion

Despite the common belief that the built environment is a protective measure in terms of air quality, our research suggests that the

| Event                  | Indoor vs. rooftop readings | Air handling room vs. rooftop readings |
|------------------------|-----------------------------|---------------------------------------|
| **Intercept**          | **Coefficient**             | **R²**                                 |
| Inversion              | 0.216571 (9.31e-05)**       | 0.294152                               |
|                        | (<2e-16)**                  | (<2.2e-16)**                           |
| Wildfire               | −0.522233                   | 0.771900                               |
|                        | (<2e-16)**                  | (7.87e-12)**                           |
| 4th of July            | 0.061556                    | 0.279183                               |
|                        | (<2e-16)**                  | (<2.2e-16)**                           |
| Private fireworks      | 2.888339                    | 0.382894                               |
|                        | (<2e-16)**                  | (<2.2e-16)**                           |

For statistically significant results: *** = $p \leq 0.001$.

**Table 2**

Intercept, coefficient, and $R^2$ values for each study event; $p$-values are listed in parentheses, and for $R^2$ values, these are the $p$-values of the F-statistic. For statistically significant results: *** = $p \leq 0.001$.

#### Fig. 4.

Minute-resolved relationship between indoor and outdoor air quality for study events: a) December 7th–12th inversion, b) August 23rd-24th wildfire, c) 4th of July fireworks, and d) Private fireworks event on August 17th. The symbol color corresponds to AQI levels for the y-axis (office or air handling room) data. The axes are different for each panel.
relationship between indoor and outdoor air quality varies in relevant and consequential ways. We compared an average baseline day to three types of random, but elevated pollution events and found that the relationship between indoor and outdoor pollution is pollutant-specific and indoor conditions may be just as harmful to human health, especially in the short term. Each case we presented illustrates how the patterns of indoor and outdoor air quality adopt specific patterns based on each unique pollution event and additional research will be needed to further classify the regularity of these patterns. Since the “at-home” work force is expected to grow following the pandemic, indoor air quality is of growing importance and public policy may need to be more adaptive and nuanced to assure human health and well-being is protected during elevated pollution events. The findings from this research have substantial technical and public health implications.

### 4.1. Technical implications

Since the SLV has been found to be in non-compliance for air quality standards in both PM$_{2.5}$ and ozone, the state has been developing a State Implementation Plan (SIP) to address this issue (Utah Department of Environmental Quality, 2018; Utah Division of Air Quality, 2018). Technical knowledge and baseline data on PM$_{2.5}$ is of great value locally and, in this study, we add to this technical understanding. For instance, we confirmed that during inversion events, the majority of PM$_{2.5}$ readings are from secondary particulate matter (Baasandorj et al., 2017; Lareau et al., 2013), which is particulate matter that is not directly emitted but instead is generated through chemical reactions facilitated by stable meteorological conditions. When the conditions are drastically changed indoors due to increased temperature and decreased relative humidity, a large amount of PM may decompose into its precursors. While it is possible that the outdoor PM$_{2.5}$ mass concentrations observed during this time are slightly overestimated due to the high relative humidity present, the magnitude of the differences observed between the outdoor and indoor sensor are significantly beyond the potential impact on concentrations giving us a high degree of confidence in our findings. However, wildfire smoke is primary (directly emitted) PM that does not dissociate due to changing conditions and is able to pass through building filtration, without decomposing, leading to orange air quality levels indoors. This could lead to significant health concerns for sensitive groups include young, elderly, and populations with prior conditions including asthma, cystic fibrosis (CF), and COPD. Wildfire episodes are expected to increase in the upcoming decades (Schoennagel et al., 2017) and our research shows that buildings offer little air quality protection from wildfire events. These technical considerations could be helpful to local and state authorities.

Considering the impacts of outdoor pollution events on indoor air quality, this research also has important implications for building health, filtration systems, and ventilation schedules, especially in public spaces where the health and well-being of its occupants must be assured (e.g., government buildings, schools, hospitals, etc.). Through the use of long-term direct measurement in air quality sensing, we have demonstrated that not all pollutants are created equal in terms of their ability to enter a building. Our research, and others like it, will be essential in the effort to design and implement pollution abatement measures and quantifying their effects to best inform the policy process. Having a baseline inventory of the emissions processes found in urban settings can also help to establish risk assessment and management programs. Therefore this (and future) studies can advance (or facilitate) modeling to predict indoor air quality based on outdoor pollutant levels and nature of event (i.e., wildfire, inversions, fireworks).

### 4.1.2. Public health and policy implications

Our study also has important implications for public policy and public health. This research suggests that air pollution policy many need to differentiate and carefully define policy reflecting the trajectory and implications of different elevated pollution events in order to best protect the public in reflection of these unique characteristics. For example, tracking air quality at this level of granularity could greatly enhance our ability to highlight geographical areas whose inhabitants are most exposed to poor air quality or to identify how many people in an area are exposed to concentrations of pollution exceeding air quality guidelines. Research on children is advancing in this area to better understand

#### Table 3

| Study period | Rooftop vs. regulatory sensor readings | Intercept | Coefficient | R²  |
|--------------|--------------------------------------|-----------|-------------|-----|
| Complete     |                                      | -0.680770| 0.949783    | 0.6326  |
| Inversion    |                                      | <2e-16    | <2e-16      | <2e-16  |
| Wildfire     |                                      | 1.41e-09  | 1.34973     | 0.59269 |
| 4th of July  |                                      | 0.0224*   | 9.67e-10*** | 0.7471  |
| Private fires|                                      | -0.9470   | 0.8906      | 0.606  |

#### Fig. 5

Hour-resolved air quality: a) Full study period with the green and black lines correspond to the Hawthorne Division of Air Quality and USL rooftop sensors, respectively, and b) Direct comparison via X-Y plot. The symbol color corresponds to AQI levels for the y-axis (USL rooftop) data. The axes are different for each panel.
short-term (Mendoza et al., 2020; Mullen et al., 2020) and lifetime exposure impacts (Berhane et al., 2011), but other groups are also at risk of higher-than-average exposure rates. Our findings could be used to advance such research by describing the exposure of population subgroups such as children, elderly, medically vulnerable groups (e.g., COPD and asthma patients), and essential workers (e.g., military personnel, first responders).

4.1.3. Future research

A follow-up study is currently underway at the Utah State Hospital in Provo, Utah. An air quality sensor has been located on the rooftop of the Pediatric building. Two indoor air quality sensors have been placed in rooms belonging to the dormitory and daycare wings as they have different air handlers and will assess the impact of different ventilation and filtration technologies on indoor air quality. This study will help in the understanding of potential benefits of different HVAC systems and identify possible improvements to increase occupant health and safety. Future study on the performance of various filtration options and the differences between 100% outside air systems and recirculated air systems would be beneficial to understanding effective ways to mitigate pollution travelling from outside into workspaces.

4.2. Conclusions

This year-long study illustrates an array of ways that elevated pollution events interact with the protective effects that buildings have against air pollution for its occupants. The current results show that while the Unified State Laboratories building provided a relatively protective environment for its occupants during wintertime inversion events, the indoor air quality was comparable to the outdoor air quality during wildfire and firework events. These differences are partially attributable to the physical and chemical cycles responsible for the generation and disassociation of secondary particulate matter during wintertime inversion events. It is also likely that some of the wildfire and fireworks smoke particles are too small to be filtered with the current building filtration systems.

CRediT authorship contribution statement

Daniel Mendoza: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. Tabitha M. Benney: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. Sarah Boll: Validation, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Event timeline and table of abbreviations

| Year | Event Description |
|------|-------------------|
| 2018 | • April 30: Sensors installed. |
|      | • July 4–5: Firework event (Fig. 3.c). |
|      | • August 17: Private firework event (Fig. 3.d). |
|      | • August 23–24: Wildfire Event (CA, MO, CO – all had major fire events) (Fig. 3.b). |
|      | • September 15: Wildfires push air quality beyond orange into red. |
|      | • November 22: Lingering wildfire pollution is cleared out around 7 am until noon as average wind speed went from 2 to 3 kph for the week, up to 25 kph and cleared the smoke out temporarily. |
|      | • December 7–12: Winter Inversion Event (Fig. 3.a). |
|      | • December 17: High wind gusts and associated air quality cleanup. |

| Year | Event Description |
|------|-------------------|
| 2019 | • January 8–16: Substantial inversion (not included). |
|      | • January 30: Mini inversion event. |
|      | • May 30: Study ends. |

Table A.1

| Table of abbreviations. | |
|-------------------------|------------------|
| Air Handling Unit (AHU)  | BSL Chronic obstructive pulmonary disease (COPD) |
| Cystic fibrosis (CF)     | Heating, Ventilation, and Air Conditioning (HVAC) |
| Chronic obstructive pulmonary disease (COPD) | Fine particulate matter (PM2.5) |
| State Implementation Plan (SIP) | Salt Lake Valley (SLV) |
| Unified State Laboratories (USL) |

Appendix B. Summary of HVAC system in the Utah Unified State Laboratory Building, Module 1

Air is delivered to lab spaces by Phoenix Air valves and by variable air volume box terminal units for office spaces. Both air delivery valves include hydronic reheat coils, indicating that air delivered to a space can be warmed directly prior to delivery to the space.

The air flow is a single pass 100% outside air design. The air is pulled by the air handling units (AHUs) through a set of louvers, filters, a heat recovery coil, a glycol preheat coil, passes through the AHU and is then pushed through indirect evaporative cooling coil, a chiller water cooling coil, a direct evaporative cooling coils, a second set of louvers (see Fig. B.1) before being pushed further through the duct work to the various terminal units and delivered to the various spaces through a diffuser grill.

This could be relevant to the amount of particulate matter that travels from the outside to workspaces as it averaged 10 points of resistance to the air flow that is delivered to the space, in addition to the filter bank which is designed to remove particulate matter from the air stream. This air path is very typical for the laboratory building. For a typical office building this air path is also very common with the one difference that office buildings try to recover air that has already been conditioned and recirculate it as an energy savings measure. Minimum air flows for various configurations of ventilations systems and building typologies are standardized through ANSI/ASHRAE Standard 62.1–2019. It is possible that in a recirculated air delivery system less pollutants would enter the workspace and worthy of further investigation.

3 Rocky Mountain Power Savings and Incentive Report Unified State Lab Persistent Commissioning Report; Ezra Nielsen, June 28, 2019.

4 ANSI/ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air Quality, https://www.ashrae.org/technical-resources/bookstore/standards-621-622
Fig. B.1. Air pathway through the Air Handling Units at Unified State Labs.

Appendix C. Comparison between USL air quality sensors and a nearby regulatory sensor

Fig. C.1. Hour-resolved impact of elevated pollution events on air quality: a) December 7th–12th inversion, b) August 23rd-24th wildfire, c) 4th of July fireworks, and d) Private fireworks event on August 17th. The green and black lines correspond to the Hawthorne Division of Air Quality and USL rooftop sensors, respectively. The horizontal lines correspond to AQI levels. The vertical scales are different for each event.
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