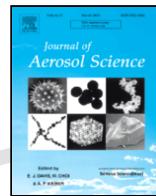




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## Technical note: Understanding the effect of COVID-19 on particle pollution using a low-cost sensor network

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### ABSTRACT

The 2020 coronavirus pandemic and the following quarantine measures have led to significant changes in daily life worldwide. Preliminary research indicates that air quality has improved in many urban areas as a result of these measures. This study takes a neighborhood-scale approach to quantifying this change in pollution. Using data from a network of citizen-hosted, low-cost particulate matter (PM) sensors, called Air Quality & yoU (AQ&U), we obtained high-spatial resolution measurements compared to the relatively sparse state monitoring stations. We compared monthly average estimated PM<sub>2.5</sub> concentrations from February 11 to May 11, 2019 at 71 unique locations in Salt Lake County, UT, USA with the same (71) sensors' measurements during the same timeframe in 2020. A paired *t*-test showed significant reductions (71.1% and 21.3%) in estimated monthly PM<sub>2.5</sub> concentrations from 2019 to 2020 for the periods from March 11-April 10 and April 11-May 10, respectively. The March time period corresponded to the most stringent COVID-19 related restrictions in this region. Significant decreases in PM<sub>2.5</sub> were also reported by state monitoring sites during March ( $p < 0.001$  compared to the previous 5-year average). While we observed decreases in PM<sub>2.5</sub> concentrations across the valley in 2020, it is important to note that the PM<sub>2.5</sub> concentrations did not improve equally in all locations. We observed the greatest reductions at lower elevation, more urbanized areas, likely because of the already low levels of PM<sub>2.5</sub> at the higher elevation, more residential areas, which were generally below 2  $\mu\text{g}/\text{m}^3$  in both 2019 and 2020. Although many of measurements during March and April were near or below the estimated detection limit of the low-cost PM sensors and the federal equivalent measurements, every low-cost sensor (51) showed a reduction in PM<sub>2.5</sub> concentration in March of 2020 compared to 2019. These results suggest that the air quality improvement seen after March 11, 2020 is due to quarantine measures reducing traffic and decreasing pollutant emissions in the region.

### 1. Introduction

Since the COVID-19 pandemic led to large-scale reductions in the global economy, researchers have reported notable reductions and traffic, and seismic noise, which is an indicator of human activity (Lecocq et al., 2020; Xiao et al., 2005), and improvements in air quality, especially over quarantined regions. For example, in Los Angeles, Seattle, and New York, ground-level NO<sub>2</sub> concentrations were 30% lower during late March of 2020 than long-term averages for the same timeframe (McQuate and Gourley, 2020). Similar reductions in NO<sub>2</sub> have also been reported globally from ground-level and satellite measurements (NASA, 2020a, 2020b;

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Myllyvirta and Sahiya, 2020; EEA (European Environment), 2020). However, the effects of COVID-19 on fine particulate matter (PM<sub>2.5</sub>, particulate matter with an aerodynamic diameter of 2.5  $\mu\text{m}$  and smaller) concentration have varied with some locations reporting reductions (He et al., 2020; McQuate and Gourley, 2020) and others reporting increases or no change (McQuate and Gourley, 2020; EEA (European Environment), 2020).

Numerous studies have linked increases in PM<sub>2.5</sub> levels to adverse health effects including cardiopulmonary disease and premature mortality (Liang et al., 2018; Pope et al., 2011). A recent study found that a 1  $\mu\text{g}/\text{m}^3$  increase in PM<sub>2.5</sub> concentration is associated with a 15% increase in the COVID-19 death rate (based on a 16-year average) (Wu et al., 2020). Consequently, understanding the effects of COVID-19 on air quality is important for understanding the risks of COVID-related mortality and for public health in general.

Thus far, researchers studying the effects of COVID-19 on PM<sub>2.5</sub> concentrations and the relationship between COVID-related mortality and air quality have used air quality information from sparsely distributed government monitoring stations, city-wide averages from low-cost sensors as proxies for federal reference methods (FRMs), or inferred concentrations from satellite measurements of aerosol optical depth (AOD) (Fan et al., 2020; He et al., 2020; Myllyvirta and Sahiya, 2020). Satellite measurements of AOD have a resolution of 1 km<sup>2</sup>, and inferring PM<sub>2.5</sub> concentration from AOD can be complicated by confounding factors such as humidity, aerosol composition, and the altitude of the aerosol layer (Duncan et al., 2014; NASA, 2020a, 2020b). Sparsely distributed government monitoring stations or inferred from satellite imaging can fail to capture localized PM<sub>2.5</sub> gradients within an urban area (Apte et al., 2017; Kelly et al., 2021; Steinle et al., 2013).

In this technical note, we evaluate how PM<sub>2.5</sub> concentrations from the AQ&U (Air Quality & yoU) network of low-cost sensors can help in understanding how COVID-19 restrictions are affecting air quality at a neighborhood level and whether this information can contribute to the weight of evidence regarding the effect of COVID-19 on PM<sub>2.5</sub> levels in this region.

## 2. Methods

This study focuses on Salt Lake County, UT, USA, a region that periodically experiences the highest PM<sub>2.5</sub> levels in the country (KUTV, 2017), in particular during winter time persistent cold air pools (PCAPs) (Whiteman et al., 2014). This county has a population of 1,152,633 (U.S. Census Bureau, 2020), and it occupies a mountain valley that is bounded by the Wasatch Mountains to the east, the Oquirrh mountains to the west, and the Great Salt Lake to the northwest. The valley floor lies at an elevation of 1283 m. This county is comprised of approximately 56% industrial/commercial land, 22% natural/public land, 17% residential, and less than 5% institutional, agricultural, and other (Salt Lake City GIS Open Data, 1442). This study area contains four state monitoring stations and a network of approximately 100 low-cost particulate matter sensors (Becnel et al., 2019a, 2019b).

In this manuscript, we evaluate the effects of the COVID-associated restrictions on PM<sub>2.5</sub> concentrations in the Salt Lake Valley by comparing three months of measurements from 2020 (February 11 to May 11) to corresponding time periods in 2019 for the low-cost sensor network and to the corresponding previous 5 years for the state monitoring stations. We focus on comparing 2019 and 2020 for the AQ&U low-cost sensor network because sufficient numbers of sensors were available beginning in 2019 and this network enables us to understand how COVID-associated restrictions affect PM<sub>2.5</sub> concentrations at a neighborhood scale.

In addition to the low-cost sensor network, we use measurements collected by the state, including PM<sub>2.5</sub> measurements from gravimetric federal reference methods (FRM; Thermo Scientific Partisol™ 2025i Sequential Air Sampler) and federal equivalent methods (FEMs; Thermo Scientific 1405-F tapered element oscillating microbalance, TEOM, and Thermo Scientific Sharp 5030i) at four Utah Division of Air Quality (DAQ) monitoring stations. Three of the DAQ stations, Hawthorne, Rose Park, and Copperview, are located in urban residential areas, and one station, Herriman is located in a suburban residential area. All stations reside in Salt Lake County (Utah, USA). When evaluating the state monitoring station results, we compared February 11 to March 10 (considered as February), March 11 to April 10 (considered March), and April 11 to May 10 (considered April) for each month in 2020 to the previous 5 years (2015–2019). Hourly PM<sub>2.5</sub> FEM measurements were used when available, and 24-h measurements (FRM) were used if they were available and if hourly measurements were unavailable. Some stations only operated during a portion of the study period (Table 1). The comparison of the PM<sub>2.5</sub> concentrations from the DAQ stations was performed using a two-tailed, student's t-test assuming unequal variance.

**Table 1**  
State monitoring stations included in this evaluation. All the instruments are made by Thermo Fisher Scientific.

Station	EPA AQS ID	Latitude	Longitude	Elevation (m)	Available data	PM2.5 measurements
Hawthorne (HW)	49-035-3006	40.7364	-111.8722	1306	2015–2020	Hourly TEOM 1405-F (2015–2018); Hourly Sharp 5030i (2019–2020); Daily Partisol™ 2025i Sequential Air Sampler.
Rose Park (RP)	49-035-3010	40.7842	-111.9310	1295	2015–2020	Hourly Sharp 5030i (2019–2020); Daily Partisol™ 2025i Sequential Air Sampler.
Herriman (H3)	49-035-3013	40.4954	-112.0341	1530	2016–2020	Hourly TEOM 1405-F (2015–2018); Hourly Sharp 5030i (2019–2020).
Copperview (CV)	49-035-2005	40.5980	-111.8958	1343	2019–2020	Hourly Sharp 5030i (2019–2020).

Table S-1 provides a summary of the monthly average meteorological conditions and PM<sub>2.5</sub> concentrations at the Hawthorne monitoring station from February 11 to May 11, 2019. Fig. S-1 provides the monthly wind roses for the same time period. These wind roses show the typical diurnal pattern for this region (Stewart et al., 2002).

This study relies on a university-community network of low-cost, air-quality sensors, called AQ&U (Kelly et al., 2021; AQ&U, 2020). This network is based on the AirU package. Each AirU includes a custom 4-layer printed circuit board with a TI CC3200 micro-controller and a 32-bit ARM® Cortex® M4 Core and WiFi capabilities. The AirU contains a Plantower PMS3003 optical particle counter, TI HDC1080 temperature/humidity sensor, TI OPT3001 light sensor, SGX MiCS 4514 reducing/oxidizing gas sensor, GlobalTop PA6H22 GPS module, real-time clock, and micro-SD card (Becnel et al., 2019a). The Plantower 3003 estimates PM<sub>2.5</sub> concentration based on light scattering at a laser wavelength of  $640 \pm 10$  nm. Air continuously flows into the Plantower through a fan that operates at a flow rate of 0.1 L/min. Prior to deployment, all sensors are evaluated in a laboratory test chamber to ensure that malfunctioning sensors are not deployed (Sayahi et al., 2019a). Several studies indicate that the Plantower PM<sub>2.5</sub> measurements correlate well with FEMs in Salt Lake City and other locations when PM<sub>2.5</sub> levels exceed the (Bulot et al., 2019; Feenstra et al., 2019; Kelly et al., 2017; Sayahi et al., 2019b) sensor's limit of detection ( $1-5 \mu\text{g}/\text{m}^3$  PM<sub>2.5</sub>). (Bulot et al., 2019; Sayahi et al., 2019b).

A total of 71 AirU sensors were operating in the same locations during the study period in both 2019 and 2020 with sufficient data for analysis in at least one month of our study period. We compared each sensor's monthly average PM<sub>2.5</sub> concentration in February, March, and April 2020 to those measurements in 2019 using a paired *t*-test. For each month after screening for completeness ( $>75\%$ ) and correcting for hygroscopic growth, the comparison included sensor data from the following number of sensors: 65 in February, 51 in March, and 53 in April. Our study months were defined in the same manner as the state data, lasting from the 11<sup>th</sup> of the first month through the 10<sup>th</sup> of the next month.

Aerosol optical properties affect measurements of PM mass concentration from light-scattering-based aerosol instrumentation, like the Plantower sensors in this study. Many investigators apply a correction factor to light-scattering PM mass measurements to improve their estimates; these are based on particle composition and hygroscopic growth or co-location with FEM measurements of PM<sub>2.5</sub> (Jiao et al., 2016; Castell et al., 2017; Zheng et al., 2018, pp. 4823–4846; Malings et al., 2020). Figs. S-2 and S-3 and Table S-2 and S-3 show the scatter plots and linear fits of several co-located AirU sensors with state-operated FEMs during the study period. These fits were performed after removing outliers using the interquartile range method (Schwertman et al., 2004).

The AirUs correlate poorly to moderately with the FEMs during March and April of 2020 ( $R^2$  0.38–0.64, Fig. S-3 and Table S-2 and S-3, although sensor S-A 187 appeared to malfunction in 2020 and was uncorrelated with the FEMs during this period). The correlations are slightly better in March and April of 2019 ( $R^2$  of 0.39–0.84, Fig. S-2, Tables S-2 and S-3), likely due to the higher PM<sub>2.5</sub> concentrations in 2019 (Fig. 1). During March and April of 2019 and 2020 many of the hourly average PM<sub>2.5</sub> concentration measurements were below  $5.1 \mu\text{g}/\text{m}^3$  (77.8% and 77.2% in 2019 and 2020, respectively). At concentrations below  $5.1 \mu\text{g}/\text{m}^3$ , two FEMs co-located at the Hawthorne monitoring station do not correlate well with each other ( $R^2$  of 0.27–0.34) (Fig. S-4, Table S-4). Consequently, rather than applying a correction factor from co-located FEM measurements, we apply the method described by Malings et al. to correct light-scattering particle concentrations for hygroscopic growth (Malings et al., 2020). This method is described in the supplementary material and relies on the particle composition, literature data for individual component hygroscopic growth factors, temperature, relative humidity (RH), and the volume-weighted particle diameter for this region and season.

### 3. Results and discussion

Fig. 1 compares the month by month average PM<sub>2.5</sub> measurements at the four state monitoring stations in 2020 to the previous 5 years, when available. The greatest reductions are evident in March of 2020 when the state issued its “Stay safe, stay home” guid-

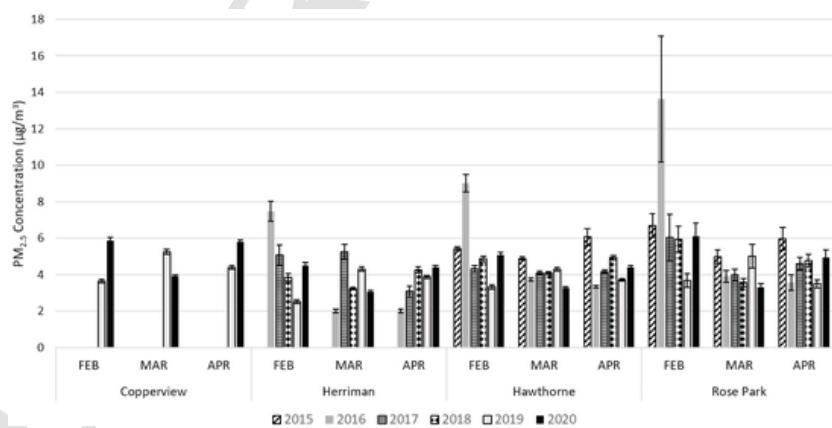


Fig. 1. Month-by-month average PM<sub>2.5</sub> concentrations measured at four state monitoring stations in Salt Lake County from 2015 to 2020, where data was available. Error bars represent standard errors.

ance (Utah Division of Emergency Management, 1630), the University of Utah (which had 31,818 students and 4463 faculty members in 2019) (The Office of Budget and, 2020) transferred students to online learning and required all non-essential employees to work from home (University of Utah, 2020), and the ski resorts closed (Utah, 2020). The decreases at the FEMs ranged from 18.4 to 25.4%, and the differences were all statistically significant compared to the previous 5-year average ( $p < 0.001$ , Table S-6). Only two stations, Hawthorne and Rose Park, collected 5 years of measurements, and these two stations exhibited similar reductions, 22.3–22.9%. Generally, the Rose Park location exhibited the highest PM<sub>2.5</sub> concentrations during this study period. It is located in a lower middle income area (Mullen et al., 2020), within 1 km of the I15 interstate, 5 km of an industrial complex that includes a refinery complex, and 3 km of gravel operations.

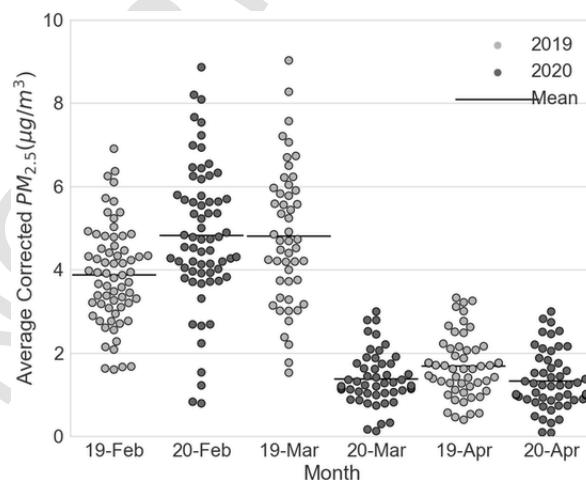
This March time period also corresponded to statistically significant reductions in passenger vehicle traffic in the Salt Lake Valley. Traffic counts along I-15 on the Wasatch Front during this period were 31.6% lower than in 2019 on average (Table S-7). (Utah Department of Transportation, 1334) Traffic into and out of Little and Big Cottonwood canyons (the locations of four major ski resorts) also decreased, by about 50% and 30%, respectively. However, truck traffic at I-15 entry points actually increased slightly in March 2020, with an average of 109% of day-of-the-week (DOW) values from January 1–March 10, 2020, compared to all-vehicle traffic, which was 82.7% of the average DOW volume (Table S-8).

In February 2020, PM<sub>2.5</sub> concentrations were higher than those in 2019 (Table S-6), although when comparing the measurements to the previous 5-year average the differences are not statistically significant ( $p > 0.05$ ). This region experiences persistent cold air pools (PCAPs) that occur periodically between November through February (Whiteman et al., 2014). These PCAPs are associated with elevated PM<sub>2.5</sub> concentrations and atmospheric stability. The occurrence and severity of PCAPs exhibits large year-to-year differences in severity (Whiteman et al., 2014). Consequently, comparing the 2020 measurements to the previous 5-year average is likely more meaningful during the PCAP season. It also suggests that prior to the COVID-related restrictions, PM<sub>2.5</sub> concentrations in 2020 were similar to previous levels in the corresponding month. During February 2020, truck traffic near I-15 entry points was, on average, 104% of DOW volumes and all-vehicle traffic was, on average, 110% of DOW volumes (Table S-8) (Utah Department of Transportation, 1334). Along I-15 in Salt Lake County, traffic volumes increased by an average of 0.2% compared to February 2019, and traffic through Little and Big Cottonwood increased by 5.1 and 10.2% respectively (Table S-7). However, these increases were not statistically significant ( $p > 0.05$ ).

In April 2020, PM<sub>2.5</sub> concentrations were higher than the previous five-year average at three out of the four monitoring stations (all but Hawthorne). In the two locations with 5 years of measurements, the differences were not statistically significant. Traffic volumes along the Wasatch Front exhibited a 33.5% decrease compared to April 2019 (Table S-7). (Utah Department of Transportation, 1334) Interestingly, while Little Cottonwood traffic was 37.5% lower than in 2019, Big Cottonwood traffic increased by 26.5% during this period (Table S-7). This may suggest that citizens were beginning to return to regular recreational activities during this period. Truck traffic in April was at an average of 102% of the DOW volumes, while all-vehicle traffic was 73.9% of the DOW (Table S-8). It is important to note that state PM<sub>2.5</sub> concentrations were sometimes below the FEM detection limit of 2  $\mu\text{g}/\text{m}^3$  in 2019 and 2020 (28.4% and 17.2% of measurements in February, 26.8% and 39.0% in March, and 27.2% and 14.1% in April, respectively).

Sufficient low-cost PM<sub>2.5</sub> measurements are only available for 2019 and 2020, but they confirm the trends observed at the state monitoring stations with lower PM<sub>2.5</sub> concentrations in March 2019 compared to 2020, similar PM<sub>2.5</sub> concentrations in April but higher PM<sub>2.5</sub> concentrations in February (Fig. 2) (see Fig. 3).

During March of 2020, every low-cost sensor showed a decrease in estimated PM<sub>2.5</sub> concentration compared to the same sensor in 2019. These paired differences were statistically significant ( $p < 0.001$ ). Averaged across all sensors, concentrations fell by 71.1%. Replacing values less than 1 with 1  $\mu\text{g}/\text{m}^3$ , the Plantower PMS sensors' limit of detection, yields a reduction of 67.8% (Fig.



**Fig. 2.** Monthly average corrected PM<sub>2.5</sub> concentrations for February, March, and April 2019 compared to 2020 for each low-cost sensor that had 75% complete measurements in 2019 and 2020. Mean values are displayed as black bars within each bee swarm.

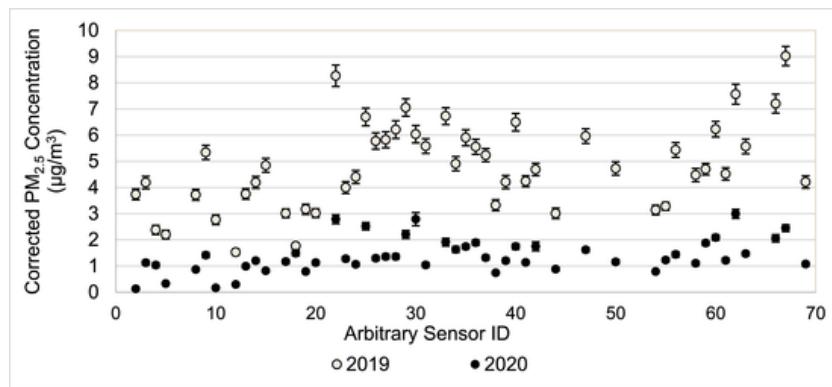


Fig. 3. Comparison of March 11 to April 10 average corrected PM<sub>2.5</sub> concentrations for paired sensors that remained in the same location and had 75% complete readings during 2019 and 2020. Error bars denote standard errors.

S-6). The low-cost sensors are suggesting greater reductions than those observed at the state monitoring stations. This may be due to the low PM<sub>2.5</sub> concentrations during the study period, many of which are at or near the sensors' limit of detection as well as the FEM's limit of detection. However, the relative measurements can still support the evidence of lower PM<sub>2.5</sub> concentrations, even if exact reductions are difficult to quantify.

Meteorology can affect ambient levels of PM<sub>2.5</sub>, and their relationship can be complex and non-linear. It is possible that meteorology plays a role in the PM reductions shown by the low-cost sensor network and the state measurements. For example, relative RH can affect light-scattering based PM measurements, particularly from low-cost sensors (Wang et al., 2015). However, the hygroscopic growth correction described in Malings et al., 2020 and in the supplementary material should address the effect of temperature and RH on particle light scattering (Malings et al., 2020). Windspeeds are generally low during this time frame (with average speeds of 2.12 and 2.35 m/s in 2019 and 2020, respectively) and exhibit similar directional patterns (Fig. S-1). It is possible that this increased wind speed enhanced aerosol dispersion and contributed to the lower PM<sub>2.5</sub> concentrations in 2020. Wind speed and direction play a significant role in air pollutant transport when wind speeds exceed 2 m/s in urban areas, such as this study region (Kim et al., 2015). Wind speeds exceeded 2 m/s during 42.6% of the hours in 2019 data volume and 51.2% of 2020. Precipitation was not significantly different in 2020 than 2019 for the March period, and average precipitation was lower in 2020 than in 2019 (Table S-1). (National Oceanic and Atmosphere Administration, 2020)

Fig. 4a and b show that in March of 2019 and 2020, the highest levels of PM<sub>2.5</sub> are found at the lowest elevations in the center of the valley, which is more urban and is intersected by two interstate highways, while the higher elevation, more residential and higher income areas of the valley exhibit lower levels. This difference in PM levels associated with elevation is consistent with previous studies of the effect of elevation on PM levels in this valley and in general on the adverse effect of urbanization on PM<sub>2.5</sub> concentrations (Baasandorj et al., 2017; Han et al., 2014; Mullen et al., 2020; Silcox et al., 2012). It is interesting that the greatest reductions in PM<sub>2.5</sub> concentration are generally observed in this lower elevation region of the valley (Fig. 4c). This is likely because the PM<sub>2.5</sub> concentrations at higher elevation residential areas are generally low, below 2 µg/m<sup>3</sup>. These greater reductions in PM<sub>2.5</sub> concentrations in the center of the valley occur in spite of the lack of a reduction in truck traffic, which suggests that the reductions in the other forms of traffic as well as the reduced economic activity in the area are responsible for the observations.

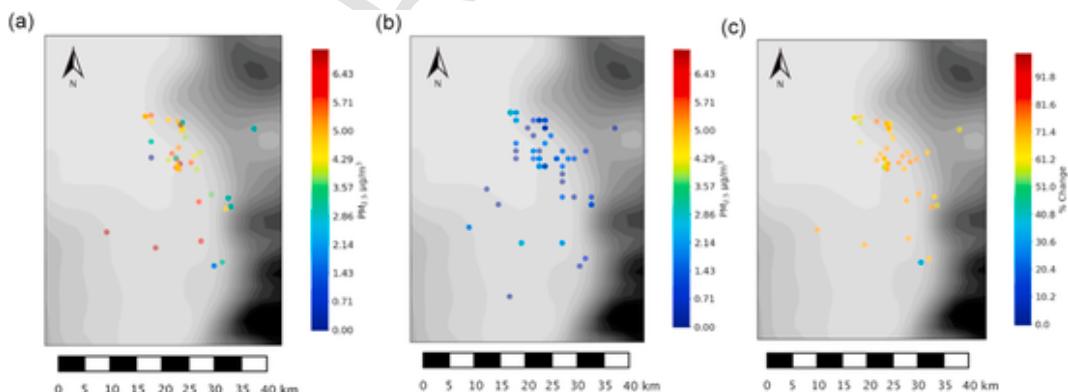


Fig. 4. PM<sub>2.5</sub> concentrations at sensor locations in the Salt Lake Valley in March 2019 (a) and March 2020 (b), and the percent reductions in PM<sub>2.5</sub> concentration (c). In calculating the percent reduction all measurements of less than 1 µg/m<sup>3</sup> were replaced with 1, which is the lower limit of detection of the PMS sensor. Some of the sensor hosts prefer to keep their locations private and are not shown on the map. The lowest elevation (1300 m) is shown in the lightest shade of gray while the highest elevation (2900 m) is shown in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

This study does have limitations because of the low PM<sub>2.5</sub> levels; many of the hourly averages are at or near the limit of detection of the Plantower PMS sensors used in the AirUs and at or near the limit of detection of the FEMs. In addition, the state monitoring stations changed the FEM measurement techniques during the past 5 years. Furthermore, the meteorological conditions could be contributing to the observed decreases in March of 2020. In spite of these limitations, all of the March measurements show a statistically significant decrease in PM<sub>2.5</sub> concentrations compared to either the 5-year average (FEMs) or compared to 2019 (low-cost sensors). These results support other recent studies that found decreases in PM concentration associated with COVID-related restrictions in some locations. A recent study evaluated ground-based measurements of PM<sub>2.5</sub> in China and found a 3 to 5-fold decrease in winter/spring of 2020 compared to the previous 3 years (Fan et al., 2020). In addition, Chauhan and Singh (Chauhan & Singh, 2020) found a 4% and 32% reduction in PM<sub>2.5</sub> concentrations in Los Angeles and New York City, respectively, in March of 2020 compared to March of 2019. In New York, they attributed some of this reduction to increased rainfall during March of 2020. In Salt Lake City, however, monthly average precipitation actually decreased in March 2020 compared to 2019, though this was not a significant difference (National Oceanic and Atmosphere Administration, 2020). The effect of rainfall, increased RH, is addressed by the hygroscopic growth correction applied in this study (Malings et al., 2020). Other studies (Chauhan & Singh, 2020) also identified decreases in PM<sub>2.5</sub> concentrations ranging from 14% to 35% in Delhi, Mumbai, Beijing, and Shanghai. On the other hand, Venter et al. (Venter et al., 2020) did not find a statistically significant decrease in PM<sub>2.5</sub> levels in the US during the first two weeks of the shutdown. Furthermore, McQuate and Gourley (McQuate and Gourley, 2020) found that some locations in the US exhibited decreases in PM<sub>2.5</sub> levels associated with the shutdown while other locations showed no change or increases.

Our results suggest that the decreases in estimated PM<sub>2.5</sub> concentration occurred in all measured locations within the Salt Lake Valley (67.8–71.1% decrease overall for March 2019 compared to March 2020) and support the state FEM measurements (21.2% reduction on average compared to the previous 5 years). These decreases also align with the decrease in traffic in this region in March (31.6% reduction on average compared to 2019). Our results suggest a greater reduction than reported by McQuate and Gourley (McQuate and Gourley, 2020), who found a slight decline in PM<sub>2.5</sub> concentrations in Utah associated with the COVID-related restrictions. However, they examined the state as a whole rather than the Salt Lake Valley. These improvements in air quality could also have important health implications. Venter et al. (Venter et al., 2020) estimated that 7400 premature deaths and 6600 pediatric asthma cases were avoided during two weeks post-lockdown in 27 countries. The majority of these avoided premature deaths were associated with reductions in PM<sub>2.5</sub> concentrations.

#### 4. Conclusions

Our results suggested that the COVID-related restrictions and corresponding reductions in vehicle traffic resulted in valley-wide reductions in PM<sub>2.5</sub> concentrations. These results support the measurements at the state monitoring stations, which also showed statistically significant reductions. The sensor measurements suggest that sites in the lowest, most urbanized locations experienced the greatest reduction PM<sub>2.5</sub> levels compared to sites in more residential areas, especially on the east side of the Salt Lake Valley. These spatial differences could be related to the very low levels of PM<sub>2.5</sub> at the higher elevation, residential sites. Our study can help support the weight of evidence regarding the effect of the COVID-19 pandemic on air quality and can subsequently support health-related studies on the associated effects.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Kelly, corresponding author, has a financial interest in Tetrad Sensor Network Solutions, which commercializes environmental sensing technologies. This company's sensors were not used in this publication.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jaerosci.2021.105766>.

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