THESIS

THE INFLUENCE OF PRESCRIBED BURNING ON SPRINGTIME $PM_{2.5}$ CONCENTRATIONS IN EASTERN KANSAS

Submitted by
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ABSTRACT

THE INFLUENCE OF PRESCRIBED BURNING ON SPRINGTIME $PM_{2.5}$ CONCENTRATIONS IN EASTERN KANSAS

Annual springtime (March - May) prescribed burning is practiced in the Flint Hills of eastern Kansas to mitigate wildfire risk, improve nutritional value of vegetation for cattle grazing, limit woody encroachment, and maintain the health of the tall grass prairie ecosystem. Smoke from these prescribed fires produces fine particulate matter ($PM_{2.5}$), degrading air quality. Smoke from prescribed fires is understudied due to their short duration and a lack of monitoring in the rural regions where prescribed burning occurs. To quantify the contribution of springtime prescribed burning to $PM_{2.5}$ concentrations in the Flint Hills and downwind regions, we deployed 38 PurpleAir $PM_{2.5}$ sensors for the 2022 burning season. We used observations from this ground-based network alongside a suite of satellite products to determine the $PM_{2.5}$ attributable to smoke. In 2022, the Flint Hills were also impacted by dust and transported smoke from high winds, drought, and wildfires in New Mexico. We separated the local and transported smoke effects for our exposure estimates. Across the low-cost sensor network, 24-hour median $PM_{2.5}$ increased by 5.2 $\mu g\ m^{-3}$ on days impacted by smoke from fires in the eastern Kansas region versus smoke-free days. We compared our findings to two existing $PM_{2.5}$ estimates derived from satellites and ground-based measurements. Satellite-based products show a similar daily smoke-driven median increase in $PM_{2.5}$ concentration and a consistent increase in seasonal average $PM_{2.5}$ concentrations in the Flint Hills region as our estimates based on in situ monitors.

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TABLE OF CONTENTS

Chapter 1

INTRODUCTION

Biomass burning is a major source of fine particulate matter ($PM_{2.5}$), which degrades air quality (Ford et al., 2018; Johnston et al., 2012; O'Dell et al., 2021). Exposure to $PM_{2.5}$ is associated with a suite of negative health effects including increased risk of cardiopulmonary emergency department visits, hospitalizations, medication use, and mortality (Cohen et al., 2017; Dockery, 2001; Pope, 2000). In the United States, wildfires are a large source of $PM_{2.5}$ in the summertime (Dennison et al., 2014; O'Dell et al., 2019). Prescribed burns are used to decrease wildfire risk (Fernandes and Botelho, 2003; Kolden, 2019), manage landscapes (Francos and Úbeda, 2021), and maintain biodiversity (Knapp et al., 2009; Nippert et al., 2021). Prescribed burning is also a source of $PM_{2.5}$ with a distinct regionally specific timing, prescribed burning in the US generally occurs in the spring and fall, when the risk of prescribed fires becoming wildfires is lower than in the summer (Brey et al., 2018; Kaulfus et al., 2017; O'Dell et al., 2021). Because prescribed fires are often smaller and of short duration, the impact of smoke from prescribed burning is less quantified (Starns et al., 2020).

Springtime burning occurs annually in the Flint Hills (FH) region of Kansas (of Health and Environment, 2022; Mohler and Goodin, 2012; Rosen et al., 2023; Scholtz et al., 2020). The FH region extends from northeastern Kansas to northeastern Oklahoma. The counties that are considered to be in the Flint Hills as defined by the Kansas Department of Health and the Environment (KDHE) include 21 counties (of Health and Environment, 2022). The counties in Kansas are Butler, Chase, Chautauqua, Coffey, Cowley, Elk, Geary, Greenwood, Lyon, Marion, Morris, Osage, Pottawatomie, Riley, Wabaunsee, Wilson, and Woodson (Figure 1.1). These counties are sparsely populated (Figure A.1; Bureau, 2023).

Fires in the springtime (March - April) are routinely used in the Flint Hills to decrease wildfire risk, increase nutrition of vegetation for livestock (Duncan et al., 2021), control invasive grass species (Alexander et al., 2021; Ditomaso et al., 2006), and maintain ecosystem diversity, resilience,

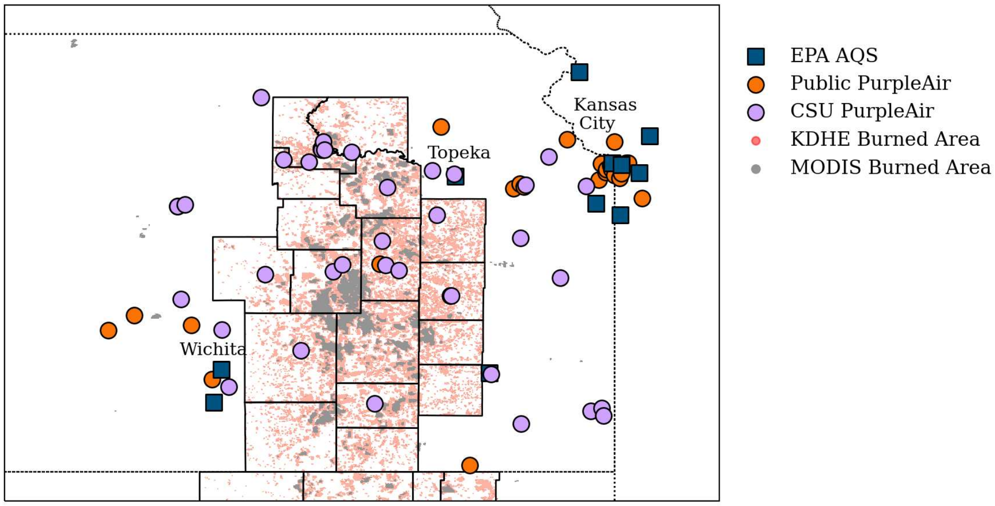

Figure 1.1: Locations of in situ $PM_{2.5}$ monitors and burned area from KDHE and Moderate Resolution Imaging Spectroradiometer (MODIS) in eastern Kansas. County lines are included for the Flint Hills counties.

and health in the tall grass prairie (Bruckerhoff et al., 2020; Ohlenbusch and Hartnett, 2000). The tall grass prairie is a rare ecosystem and is threatened by woody encroachment. Prescribed burning is practiced for abatement of this encroachment (Abrams, 1988; Morford et al., 2022; Short et al., 2019). Prescribed fires also have cultural significance in the Flint Hills, as Indigenous people practiced prescribed burning in the Great Plains to hunt for bison (Roos et al., 2018).

Although there are benefits to prescribed burning in the Flint Hills, smoke from these fires can also lead to negative health effects. Pennington et al., 2023 used fire radiative power from satellites to estimate smoke in Kansas, and they found an increase in asthma emergency department visits in Kansas from prescribed burning smoke exposure. Their study was limited due to the lack of ground-based monitoring available in Kansas. Other negative effects of prescribed burning in the Flint Hills include displacing and causing mortality of wildlife and eliminating insects critical for ecosystem processes (Kaufman and Kaufman, 2017; Pereira et al., 2021).

The areas that practice prescribed burning are often away from urban centers, and, consequently, further away from regulatory monitors (Figure 1.1; Kelp et al., 2022; US EPA, 2015), so the local $PM_{2.5}$ impacts from the prescribed burns are not fully quantifiable using only these monitors. Hence, smoke impacts in this region are still uncertain. This study seeks to understand the impact of prescribed burning in the Flint Hills on $PM_{2.5}$ concentrations. Our goal is to attribute $PM_{2.5}$ concentrations to smoke from fires in the Flint Hills.

Chapter 2

METHODS

We deployed in situ low-cost PurpleAir monitors in eastern Kansas between March and May 2022 to supplement surface US Environmental Protection Agency Air Quality System (EPA AQS) $PM_{2.5}$ measurements during the spring burning season. We also used satellite observations to identify the location of fires, distinguish the presence of smoke in the atmospheric column, and confirm elevated aerosol loading. Satellite products used in this work include MODIS burned area, Geostationary Operational Environmental Satellite Program Aerosol Optical Depth (GOES AOD) (Zhang et al., 2020), and National Oceanic and Atmospheric Administration Hazard Mapping System (NOAA HMS) smoke plumes and fire hotspots. We discuss each of these datasets and their use in the following sections.

2.1 IN SITU MONITORING

We used $PM_{2.5}$ measurements from the EPA AQS and the PurpleAir real-time air quality-monitoring networks. At the time of this study, There were 11 regulatory monitors in the area of study (Figure 1.1). These monitors were primarily located in more populated urban centers (Topeka, KS; Wichita, KS; and Kansas City, MO) outside of the counties where most of the prescribed burns occur. We used hourly and daily $PM_{2.5}$ measurements (Parameter Code: 88101) from the EPA AQS. We used measurements from both Federal Reference Methods (FRMs) and Federal Equivalent Methods (FEMs). We removed the monitoring site in Picher, Oklahoma (40-115-9007) through the entirety of our analysis due to lack of data during the campaign timeframe.

To supplement the ground-based $PM_{2.5}$ measurements from the EPA AQS regulatory monitors, we used $PM_{2.5}$ concentrations from PurpleAir. PurpleAir are low-cost sensors ($\sim$ \$300 USD per unit) that estimate $PM_{2.5}$ concentrations every two minutes. PurpleAir sensors contain two Plantower (PMS-5003) light-scattering particle sensors (channel A and B), measuring at 680 ± 10 nm. For this study, we used the raw ("CF1") $PM_{2.5}$ estimates (aerodynamic diameter of $< 2.5\ \mu$m). The sensors also include a BOSCH BME280 to measure pressure, temperature, and humidity. PurpleAir sensors have been evaluated in laboratory and field studies (Malings et al., 2020; Tryner et al., 2020; Jaffe et al., 2022; Barkjohn et al., 2021) and were found to have relatively high precision but relatively lower accuracy, especially when there was high temperatures and humidity. To improve the accuracy of the $PM_{2.5}$ concentrations from PurpleAir, we applied a correction factor (full description in Section 2.1.1).

2.1.1 PURPLEAIR MONITOR DEPLOYMENT

The existing 28 PurpleAir sensors that have publicly available data in eastern Kansas and western Missouri are primarily located away from the burning (Figure 1.1). Thus, we recruited participants to deploy 38 PurpleAir monitors throughout eastern Kansas. Most of the prescribed burning of tallgrass prairies is conducted in April. The Kansas Administrative Regulation places restrictions on burning activities, such as of waste and debris, in the 16 regulated counties of the Flint Hills during the month of April (Regulation, 2012); thus, there may be an increase in these other types of burns during March. We had participants deploy sensors for March - May 2022 to capture the entire burning season. These sensors provided spatial coverage throughout the FH where the majority of prescribed burning occurs in Kansas (Figure 1.1). We deployed 20 sensors in Flint Hills counties and 18 sensors in surrounding counties of eastern Kansas. Volunteer participants hosted the PurpleAir sensors at residences, campuses, and public buildings.

2.1.2 PURPLEAIR DATA QUALITY PROCEDURES

We conducted pre-campaign quality control of the PurpleAir sensors from October - December 2021 in Fort Collins, CO. The Plantower lasers are factory calibrated by PurpleAir. Prior to deployment in KS, we confirmed that each sensor produced accurate $PM_{2.5}$ estimates across both channels and in comparison to a Federal Equivalent Method (FEM) monitor (GRIMM EDM 180, Ainring, Germany). Sensors were co-located (< 5 m) with the GRIMM monitor for a period of 8-12 days. We conducted the quality control analysis on 10-minute averages of the raw PurpleAir data (pm2_5_cf_1). $PM_{2.5}$ concentrations during this analysis ranged from 0 to 49.2 $\mu g\ m^{-3}$.

When comparing channel A and channel B within each PurpleAir device, the correlation between channels averaged 0.99; the lowest R^2 was 0.84 (Figure A.2). The monitor with the lowest channel comparison R^2 had an average agreement with the GRIMM monitor and was deemed suitable for the field. During the calibration tests, the mean absolute difference between channels ranged across the devices from 0.18 to 1.2 µg m^{-3}. The 10-minute channel average of each sensor was strongly correlated to the 10-minute average of all sensors (mean R^2 = 0.99; mean bias = 0.05%). The mean R^2 between the 10-minute average PurpleAir and the GRIMM $PM_{2.5}$ concentrations was 0.68 (Figure A.3). The low R^2 was likely due to the lack of variability in concentrations during the co-location time period as the average mean absolute error only ranged from 1.9 to 2.6 µg m^{-3}. These findings are consistent with past studies (Magi et al., 2020; Sayahi et al., 2019).

Before analysis of the campaign data, we performed a quality check on the raw $PM_{2.5}$ concentrations from PurpleAir. We took 10-minute averages of all measurements. We then removed data with the following conditions: (1) temperature > 65 ^{o}C (0.005 % of observations), (2) relative humidity > 100% (0.0001 % of observations), (3) channel disagreement > 10% from the average of the two channels and 10 µg m^{-3} in the absolute difference between the channels (3.3% of observations), and (4) measurements > 500 µg m^{-3} (0.0017% of observations).

We applied the Barkjohn et al., 2021 correction factor to the quality checked PurpleAir field measurements. Because we removed data with concentrations > 500 µg m^{-3}, we did not use correction factor for extreme smoke concentrations (> 570 µg m^{-3}) (Barkjohn et al., 2022). Due to continuously erroneous humidity observations for one sensor (PurpleAir 1361083), we used humidity observations from a nearby PurpleAir sensor to calculate the $PM_{2.5}$ correction factor. After we applied the correction factor, some observations with high humidity and low concentrations became negative. All negative concentrations after the correction factor were set to 0 µg m^{-3} (1.87% of observations).

We calculated daytime and nighttime averages of the $PM_{2.5}$ concentrations for the hours of 7:00 to 19:00 and 19:00 to 7:00 Central Daylight Time (CDT), respectively. The time associated with observations after 13 March 2022 were shifted an hour later to account for daylight savings.

2.2 SATELLITE PRODUCTS

To investigate the extent of burning we obtained MODIS burned area and the Kansas Department of Health and the Environment Moderate Resolution Imaging Spectroradiometer (KDHE-MODIS) burned area product (Mohler and Goodin, 2012; Scholtz et al., 2020). Satellite products were essential for the identification of transported smoke. For our smoke categorization (see full description in Section 2.3), we used GOES AOD and the NOAA Hazard Mapping System (HMS) fire and smoke plume product (Rolph et al., 2009; Ruminski et al., 2023). We also compared our in situ $PM_{2.5}$ results to two satellite derived $PM_{2.5}$ products (van Donkelaar et al., 2021; Zhang and Kondragunta, 2021).

2.2.1 FIRE AND SMOKE DETECTION

We used smoke plumes and fire hotspots from NOAA HMS (Rolph et al., 2009; Ruminski et al., 2023). HMS uses polar and geostationary satellite observations along with other sources to digitize smoke plumes and fire locations. We included all smoke plumes and fire hotspots in the HMS dataset for each day of the study period. We assessed whether the smoke plumes overlapping monitors were from a small local fire or from long-range transport using the horizontal extent of the HMS plume. Large plumes that cover greater regions (i.e., all of eastern Kansas – 330 km x 250 km) are not from local fires.

We used the MODIS/Terra+Aqua Direct Broadcast Burned Area Monthly L3 Global 500m SIN Grid V061 product (Giglio et al., 2021) and the KDHE-MODIS product for the years 2001–2022 to investigate the timing and extent of the burning in Kansas (Figure 1.1). Satellite-based detection systems have difficulty detecting small short-lasting fires (e.g., Hu et al., 2016); thus, the KDHE develops seasonal burned area estimates for the Flint Hills counties using the MODIS MCD64A1 burned area product that is then also verified by field observations (Mohler and Goodin, 2012; Scholtz et al., 2020).

2.2.2 AOD AND SATELLITE DERIVED $PM_{2.5}$

To help investigate whether or not the smoke was from fires outside KS, we used GOES-16 Advanced Baseline Imager (ABI) bias-corrected AOD data at 550 nm (Zhang et al., 2020). The AOD measurements have a five-minute temporal resolution and a 2 km spatial resolution. When the smoke category was more challenging to determine, we used daily averages of AOD to help our decision-making process (Section 2.3).

AOD is a measure of the aerosol loading in the atmospheric column and not a direct measurement of surface air quality. Thus, to compare satellite observations to our surface observations, we used two satellite based $PM_{2.5}$ products. The NOAA GOES Geographically Weighted Regression (GWR) $PM_{2.5}$ product (Zhang and Kondragunta, 2021) provides hourly and daily estimates of surface $PM_{2.5}$ derived from the Suomi National Polar-Orbiting Partnership Visible Infrared Imaging Radiometer Suite (VIIRS) and GOES-16 ABI along with ground-based $PM_{2.5}$ concentrations from the EPA AQS (i.e., the blue squares in Figure 1.1). The algorithm weights the surface concentrations using GWR. To compare hourly $PM_{2.5}$ concentrations from in situ measurements and hourly $PM_{2.5}$ from the NOAA GOES GWR product, we applied our smoke designations (Section 2.3) by using the $PM_{2.5}$ from the satellite product only at the locations of the monitors. The categorization for each day was applied to all hours during that day.

We also compared our ground-based $PM_{2.5}$ measurements to the van Donkelaar et al., 2021 Monthly Hybrid $PM_{2.5}$ product (V5GL03). For 2022 data, this product uses daily best estimates of AOD retrievals from several products including the Multi-angle Imaging SpectroRadiometer (MISR), MODIS Dark Target, MODIS Deep Blue, and MODIS Multi-Angle Implementation of Atmospheric Correction (MAIAC). The best estimates of AOD are used with interpolated in situ measurements from EPA AQS, and GEOS-Chem to provide 24-hour monthly mean surface $PM_{2.5}$. We compared seasonal averages (March-May) of our ground-based measurements to the derived $PM_{2.5}$.

2.3 SMOKE ASSESSMENT

Each daily measurement was categorized by the type of smoke impacting the monitoring site (Table 2.1) using a decision tree (Figure A.6). The decision process considered the following variables: HMS smoke plumes and fire hotspots, in situ $PM_{2.5}$ measurements from PurpleAir and EPA AQS sites, in situ coarse mode concentrations (PM_{10} - $PM_{2.5}$) from EPA AQS sites, daily wind speed, categorization of the previous day, and proximity to an urban setting. A detailed description of the decision tree and other components of this process are available in Appendix A (i.e., A.4, A.5, A.6).

Table 2.1: Description of the daily category assigned to each monitoring location, the number of days in each category (monitor days), and the 10th and 90th percentile number of days per monitor.

Daily Designation	Definition	Total number of monitor days	Average number of days per monitor	10th percentile number of days per monitor	90th percentile number of days per monitor
Smoke-free	No smoke was identified in the atmospheric column.	1918	26	12	33
Eastern Kansas Smoke Impacted (EK_{only})	Smoke originating from fires only in the eastern Kansas region was in the atmospheric column.	271	4	1	7
Transported Smoke Impacted	Smoke originating from fires only outside of eastern Kansas was in the atmospheric column.	2613	35	23	43
EK+T Smoke Impacted	Smoke originating from fires both outside and within eastern Kansas was in the atmospheric column.	1080	15	8	23

For each day at each measurement site, we separated the conditions into four categories: *Smoke-free*, *EK_{only} Smoke Impacted*, *Transported Smoke Impacted*, and *EK+T Smoke Impacted* (Table 2.1). We designated the day to be *Smoke-free* when we determined no smoke to be in the atmospheric column over a given monitor. We designated a day as *Eastern Kansas Smoke Impacted (EK_{only})* when there was smoke in the atmospheric column originating from fires in the eastern Kansas region, but there was no smoke from fires outside of this region. We categorized days as *Transported Smoke Impacted* when there was smoke in the atmospheric column originating from fires outside of eastern Kansas. When we identified days where smoke originated from fires both outside and within eastern Kansas, we classified these days as *Eastern Kansas and Transported Smoke Impacted (EK+T)*. In our analysis, we combined EK_{only} and *EK+T* as EK_{all} to capture all of the days where monitors were impacted by smoke from fires within eastern Kansas, regardless of if there was also transported smoke. For our categorization, we only considered monitors within eastern Kansas and Kansas City, Missouri. This included 75 total PurpleAir sensors and EPA AQS monitors. We considered daily $PM_{2.5}$ concentrations from 7am - 7am CDT to include the impact of evening burning and smoke traveling downwind that often elevated $PM_{2.5}$ concentrations in the region into the following morning.

Figure 2.1 shows an example of our smoke categorization for 14 April 2022 alongside some of the parameters that we used to perform the categorization (HMS smoke plumes and fire hotspots, daytime $PM_{2.5}$ concentrations, daily AOD, and nighttime $PM_{2.5}$). For this case, HMS smoke plumes overlapped all of the monitors of interest and $PM_{2.5}$ concentrations were elevated (> 10 µg m^{-3}) during the daytime in southeastern Kansas. HMS fire hotspots were present to the west of these monitors; thus, we categorized the monitors for this day as either *Transported Smoke Impacted* or *EK+T Impacted.*

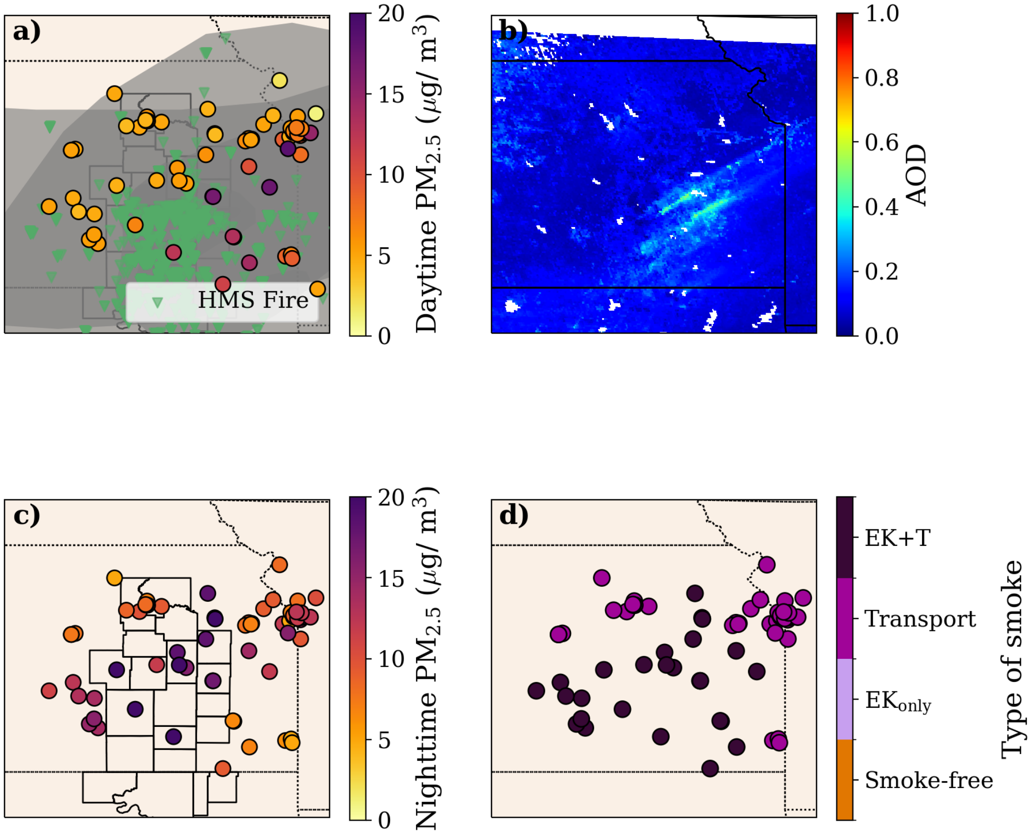

Figure 2.1: An example of d) smoke presence categorization for 14 April 2022 based on a) daily HMS smoke plumes and fires, a) daytime (7am - 7pm CDT) and c) nighttime (7pm - 7am CDT) $PM_{2.5}$ concentrations, and b) mean GOES AOD (550 nm).

Chapter 3

RESULTS

3.1 OVERVIEW OF THE 2022 BURNING SEASON

We investigated the timing and extent of the 2022 Flint Hills burning season using the KDHE burned area product and the MODIS burned area product. Both products account for the burned area within the 21 FH counties. We also examined the number of days that smoke was observed in the atmospheric column using smoke plumes from HMS.

3.1.1 THE EXTENT AND TIMING OF BURNING IN 2022

The KDHE-MODIS burned area product reported 2,112,759 acres total acres burned in the Flint Hills counties in 2022 (Figure 3.1). There is large interannual variability of burned area; 217,377 acres burned in 2013 compared to almost 3.5 million acres in 2005. The 2022 burned area was very similar to the average (2,123,419 acres) across the time period 2001-2022, suggesting that it was not an anomalous year in terms of burning.

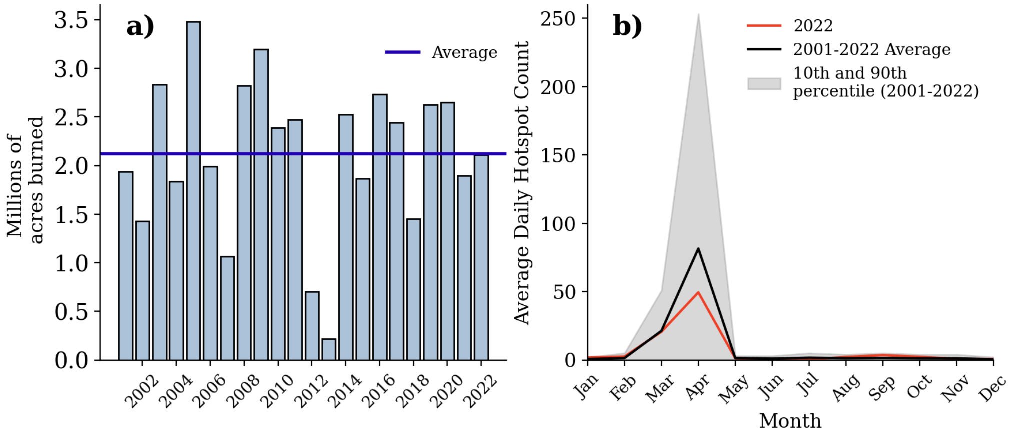

Figure 3.1: a) Acres burned from the KDHE burned area product and b) average daily hotspot count from MODIS in the Flint Hills counties from 2001-2022.

To investigate the timing of the burning, we used the hotspot fire detection from the MODIS product to assess when the burning occurred in the Flint Hills in 2022. We counted hotspots only within the designated Flint Hills counties to be consistent with the KDHE-MODIS product. The maximum average daily hotspot counts in 2022 occurred in April (50 daily hotspots), consistent with past years (2001-2022) (Figure 3.1). As mentioned previously, there are restrictions placed on types of burning other than tallgrass prairies in April. The smaller increase in fires in March may be due to an increase in waste or debris burning before restrictions begin in April.

3.1.2 TRANSPORTED SMOKE

The Flint Hills can be impacted by smoke from local burning and from transported smoke. Because wildfire season in the west typically occurs in late spring and summer; in most years, springtime smoke is primarily due to local burning. However, eastern Kansas was significantly impacted by transported smoke during spring 2022. Figure 3.2 compares the number of days there were NOAA HMS smoke plumes over our study region (HMS smoke days) in 2020, 2021, and 2022. Smoke was frequently present in the atmospheric column over eastern Kansas and northern Oklahoma during the 2022 burning season (91 total days) with a minimum of 40 and a maximum of 62 days (calculated for total map area shown in Figure 3.2). More smoke was present in the atmospheric column during 2022 than prior years, with a spatial average of 53 HMS smoke days in 2022 over eastern Kansas and northern Oklahoma, compared to 16 in 2021 and only 9 in 2020.

The increased number of days with smoke over eastern Kansas in 2022 was due to transported smoke from fires located outside of the region shown in Figure 3.2. Smoke was transported from fires located in Oklahoma, Nebraska, Texas, and New Mexico. However, New Mexico experienced two of the largest wildfires in the state's history spring 2022; the Hermits Peak and Calf Canyon fires persisted for months and consumed nearly 350,000 acres (SFNFPIO, 2022). The Hermits Peak fire started on 6 April 2022 and the Calf Canyon fire started on 19 April 2022. These fires merged and were 93% contained by 6 July 2022. This wildfire overlapped with two of the three months of our campaign. We observed smoke during this event transported to the FH area (Figure A.7 and

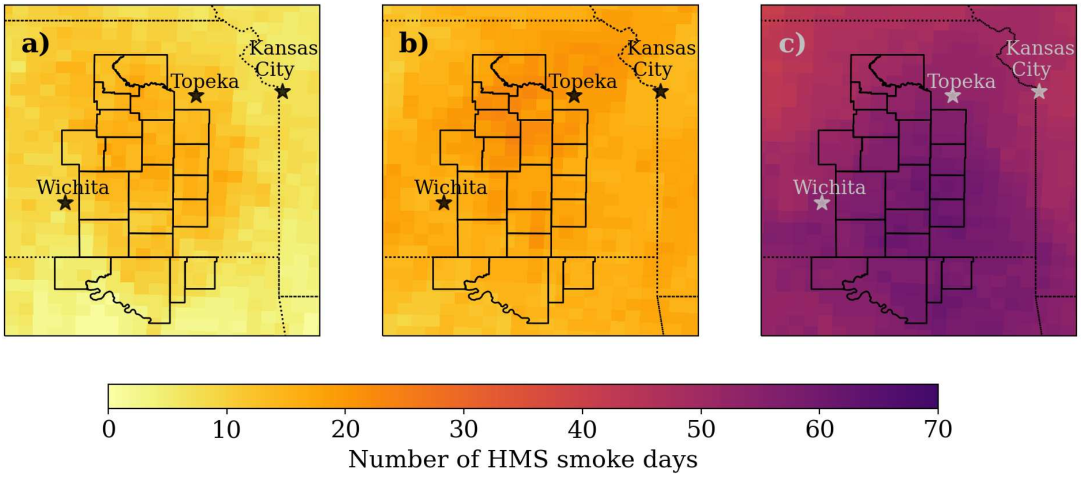

Figure 3.2: Count of days with an HMS plume in the atmospheric column on a 15 x 15 km degree grid for spring (March - May) a) 2020, b) 2021, and c) 2022.

A.8). Separating the transported smoke impact from eastern Kansas smoke impact was important in isolating the impact of local FH fires on $PM_{2.5}$ concentrations.

3.1.3 ATTRIBUTING SMOKE IN EASTERN KANSAS TO LOCAL VS. DISTANT FIRES

With the goal of attributing $PM_{2.5}$ surface concentrations to smoke, we followed the method outlined in Section 2.3 and categorized the daily smoke impact for each monitor. We then separated daily average (7am - 7am CDT) $PM_{2.5}$ concentration by the smoke categorization. In Figure 3.3, we show the distribution of daily $PM_{2.5}$ concentrations for all monitors and all days. $PM_{2.5}$ concentrations were higher on EK_{only} days compared to *Smoke-free days* (median of 9.2 vs. 4.0 µg m^{-3}); however, there were few days categorized as EK_{only} (an average of four EK_{only} *Smoke Impacted* days for each monitor (Table 2.1)). Our smoke designations show a median $PM_{2.5}$ concentration increase of 5.2 µg m^{-3} on days impacted by smoke from fires in eastern Kansas compared to days without smoke.

There was an increase in $PM_{2.5}$ during *Transported Smoke* days, relative to *Smoke-free* days, with a median concentration of 6.6 µg m^{-3} on *Transported Smoke* days. The tail of the distribution suggests that on some days, transported smoke had little impact on surface concentrations, implying that smoke was aloft. There was a similar, though slightly higher, distribution of $PM_{2.5}$ concentrations on *EK+T Smoke Impacted* days compared to the distribution of EK_{only} *Smoke Impacted* days. Because these distributions are similar and because there were few EK_{only} days at each monitor location; for the rest of the analysis, we combined EK_{only} and *EK+T* days into one designation (EK_{all}).

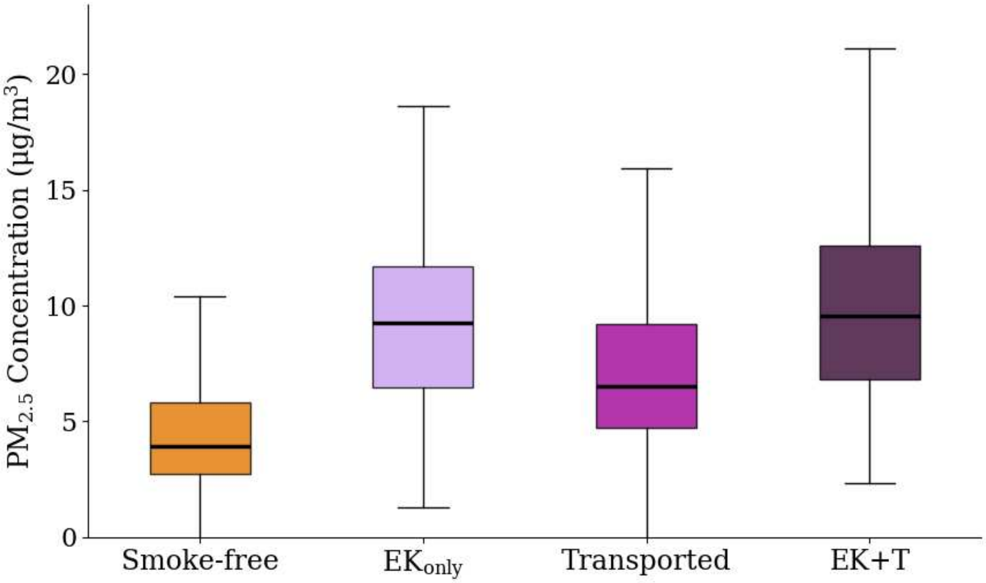

Figure 3.3: Daily averages (7am - 7am CDT) of $PM_{2.5}$ concentrations for *Smoke-free*, EK_{only} *Smoke Impacted*, *Transported Smoke Impacted*, and *EK+T Smoke Impacted* days during the spring burning season of 2022. Outliers have been excluded and the bold line represents the median for each category. The edges of the box represent the 1st and 3rd quartiles. The whiskers are +/- 1.5 times the interquartile range from the 1st and 3rd quartile. Number of monitor days in each category is shown in Table 2.1.

We assessed the statistical significance of the smoke category distributions of $PM_{2.5}$ concentrations using a Mann-Whitney U test (Mann and Whitney, 1947). This is a non-parametric test used for independent samples. We calculated the highest p-value when comparing the distributions for EK_{only} and *EK+T* (p-value = 0.04), where all other distributions had smaller p-values (p-values < 0.001). Although we still considered these categories to have statistically different distributions, this suggests that EK_{only} and *EK+T* have somewhat similar distributions of $PM_{2.5}$ concentrations, further supporting our combination of EK_{only} and *EK+T* into EK_{all}.

During the 2022 burning season, we observed substantial spatial variability in the impact of smoke on $PM_{2.5}$ across eastern Kansas. In Figure 3.4, we show the median concentration at each monitor on EK_{all} days, on Smoke-free days, and the difference. $PM_{2.5}$ concentrations during EK_{all} Smoke Impacted days ranged from 5.1 to 12.3 $\mu g\ m^{-3}$ across all monitors for the 2022 prescribed burning season. $PM_{2.5}$ concentrations during smoke-free days were relatively low across the region, ranging from 2.0 to 6.2 $\mu g\ m^{-3}$ with the maximum occurring in the Kansas City region. We considered the contribution of smoke from eastern Kansas fires to $PM_{2.5}$ concentrations to be the difference between $PM_{2.5}$ concentrations on EK_{all} *Smoke Impacted* days and *Smoke-free* days. The largest contribution of smoke to $PM_{2.5}$ concentrations occurred in the FH counties and directly east of the FH. Throughout eastern Kansas, the median contribution was 5.0 $\mu g\ m^{-3}$; and within the FH counties, the median contribution was 6.7 $\mu g\ m^{-3}$.

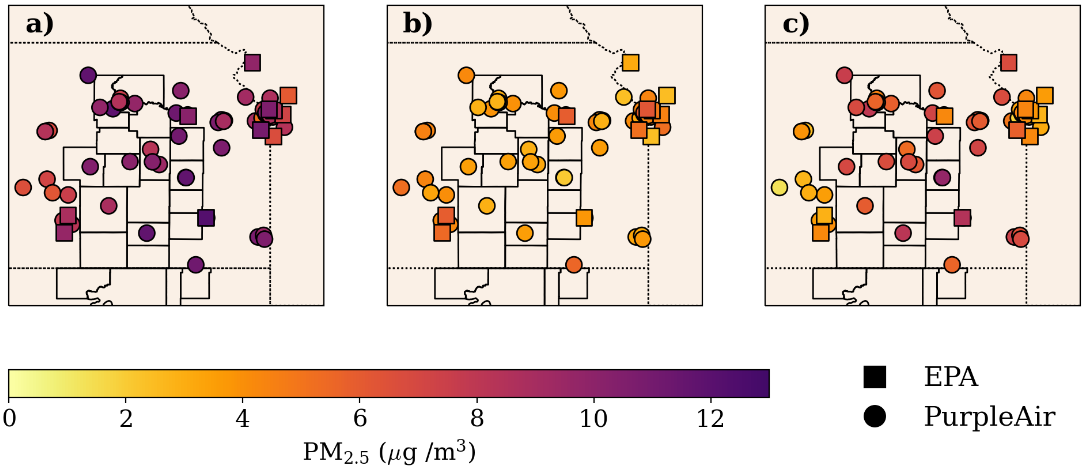

Figure 3.4: a) Median daily (7am - 7am CDT) $PM_{2.5}$ concentration on EK_{all} days, b) *Smoke-free* days, and c) the difference between the medians at each site between March - May. Marker shape indicates monitor type. Monitors with less than 10 days in either EK_{all} or *Smoke-free* impacted days were removed.

The contribution of local smoke to the springtime (March, April, May) median is 1.9 $\mu g\ m^{-3}$. EK_{all} days accounted for 26% of the total study period. Under the assumption that rangeland burning is entirely during this season (Figure 3.1) and we assume no burning during other months, then the median contribution of local smoke to the annual average is 0.5 $\mu g\ m^{-3}$. If we consider monitors only within the Flint Hills counties, the springtime contribution is 2.6 µg $^{-3}$, and the annual contribution is 0.6 µg $^{-3}$. With a higher contribution in the Flint Hills, residents in these counties are more affected by local burning.

3.1.4 COMPARING THE DIURNAL CYCLE OF $PM_{2.5}$ ACROSS REGIONS

During the 2022 burning season, we observed substantial spatial variability in the impact of smoke on $PM_{2.5}$ across eastern Kansas. We found the largest contribution of smoke to $PM_{2.5}$ concentrations to occur in the FH during the evening. In our investigation of the temporal impact of smoke, we examined $PM_{2.5}$ concentrations from ground-based measurements throughout the day, separated by smoke impact. *Smoke-free* days did not have a significant diurnal cycle; however, during EK_{all} *Smoke Impacted* days, there was often a diurnal cycle, with $PM_{2.5}$ concentrations increasing in the afternoon and building throughout the evening and overnight. For these reasons, we often considered daily averages of the ground-based concentrations to be from 7am - 7am CDT (as used in the aforementioned analysis) to estimate the contribution of smoke to $PM_{2.5}$ in the evening.

We separated monitors longitudinally into the following groups to evaluate the diurnal cycle downwind of the fires (Figure 3.5): monitors west of the FH and in the FH (pink), monitors in the area directly downwind of the FH (green), and monitors further downwind in Pittsburg, KS and the Kansas City metropolitan area (dark blue). Much less burning occurs in the counties east of the FH. The monitors west of the FH had about half of EK_{all} *Smoke Impacted* observations as the monitors in the FH counties. Most of the EK_{all} observations for the monitors west of the FH occurred during the Cottonwood Complex wildfire in Hutchinson, KS in March. For these reasons, we grouped the monitors west of the FH and in the FH.

$PM_{2.5}$ across all sites was not significantly higher in the evening during *Smoke-free* days. For the monitors west of the FH and in the FH, there was an increase from 8.5 µg m^{-3} to 15.8 µg m^{-3} during EK_{all} *Smoke Impacted* days when comparing 10:00 to 23:00 CDT. There was a smaller increase on EK_{all} *Smoke Impacted* days in the easternmost region (dark blue), with about 1.2 µg

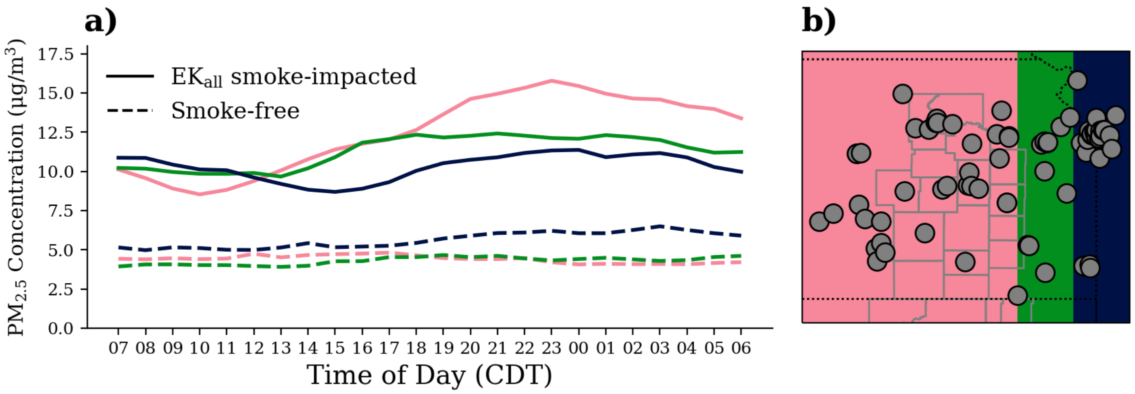

Figure 3.5: Hourly average of $PM_{2.5}$ across all ground-based monitors for March-May 2022 for *Smoke-free* days and EK_{all} *Smoke Impacted* days for three different longitudinal slices shown in b). Smoke designation was applied to every hour of the respective day.

m^{-3} of a difference. We observe a diurnal cycle, with EK_{all} $PM_{2.5}$ concentrations increasing in the evening for the monitors most impacted by the FH burning (pink). The monitors directly to the east of the FH and in Kansas City had a muted evening peak, in comparison to the FH monitors. Although there was not as significant of a diurnal cycle here, concentrations were higher on smoke impacted days versus smoke-free days.

3.1.5 IN SITU AND SATELLITE DERIVED $PM_{2.5}$ COMPARISON

To assess the accuracy of surface $PM_{2.5}$ estimates in the Flint Hills from satellite derived products, we compared two of these products (van Donkelaar et al., 2021; Zhang and Kondragunta, 2021) and the surface $PM_{2.5}$ measurements. The V5GL03 Monthly Hybrid $PM_{2.5}$ product has monthly estimates, thus, we first compare seasonal averages rather than sub-daily estimates. Both the satellite products (NOAA GOES GWR and V5GL03 Monthly Hybrid $PM_{2.5}$) and in situ measurements (Figure 3.6 and A.9) confirm elevated $PM_{2.5}$ concentrations in the FH region compared to the surrounding area during the springtime burning season each year, with some interannual variability in the estimated $PM_{2.5}$ from the satellite products (Figure 3.6). Both satellite products estimated $PM_{2.5}$ in the FH to be lower in 2020 compared to 2021, although the acreage burned was above average in 2020 and below average in 2021 (Figure 3.1). The smoke from eastern Kansas fires is more evident in the GOES NOAA GWR product (hourly estimates) compared to the V5GL03

Monthly Hybrid $PM_{2.5}$ product, with higher $PM_{2.5}$ concentrations in the FH region in 2020 and 2021.

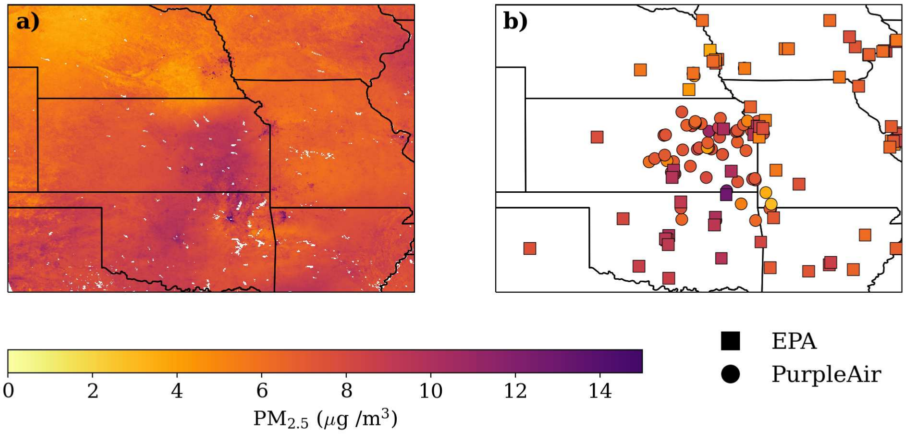

Figure 3.6: Comparison of $PM_{2.5}$ from a) the satellite derived product from NOAA GOES GWR, and b) in situ measurements from PurpleAir in the Flint Hills and EPA AQS for the entire mapped region. Marker shape indicates monitor type.

The V5GL03 Monthly Hybrid product was not available for 2022 at the time of analysis; thus, we only show the comparison between the in situ measurements to the $PM_{2.5}$ estimates from the NOAA GOES GWR product for the 2022 burning season (March - May) (Figure A.9). When comparing ground-based monitors in eastern Kansas to the NOAA GOES GWR product, we found some agreement in seasonal averages in the eastern Kansas region, with a mean absolute difference of 1.4 µg m^{-3}. This difference is relatively low, when considering the impact of transported smoke as well as local fires in the region during 2022. Despite the smoke transport, the NOAA GOES satellite product captures the higher $PM_{2.5}$ concentrations in the FH from Kansas burning compared to the surrounding areas.

The NOAA GOES GWR product also provides hourly estimates which can be compared to the hourly averaged in situ measurements. Co-located satellite estimates and in situ measurements had an average R^2 of 0.4 and a mean absolute difference of 3.5 µg m^{-3}. We also compared concentrations on smoke impacted and smoke-free days (Figure 3.7).

There was a consistent difference in the $PM_{2.5}$ concentrations on EK_{all} *Smoke Impacted* days versus *Smoke-free* days between the $PM_{2.5}$ product from the NOAA GOES GWR product (Zhang and Kondragunta, 2021) and the ground-based measurements. The difference between the average $PM_{2.5}$ concentrations in all in situ monitors for EK_{all} days and *Smoke-free* days during the satellite observation period (8:00 - 18:00) was 5.4 µg m^{-3}, and the difference of the average for $PM_{2.5}$ concentrations from the satellite product was 5.7 µg m^{-3}. The satellite product does not provide estimates overnight and is thus unable to capture the overnight peak in $PM_{2.5}$ that is observed by the in situ monitors. However, the satellite and in situ estimates have a mean percent difference of 6.5% across the entire day where there are overlapping observations for EKall days and 8.2% for Smoke-free days. The NOAA GOES GWR product hourly $PM_{2.5}$ estimates were consistent with our EK_{all} and *Smoke-free* in situ hourly averages.

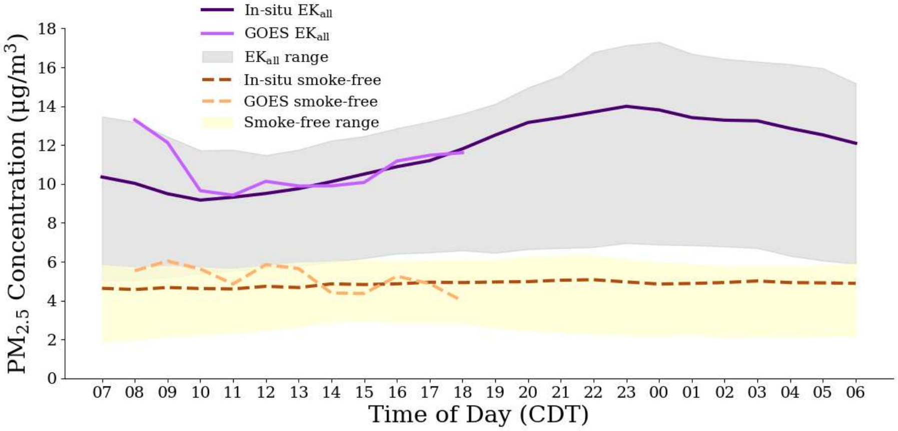

Figure 3.7: Hourly average of $PM_{2.5}$ across all ground-based monitors for March - May 2022 separated by *Smoke-free* days and EK_{all} *Smoke Impacted* days compared to the $PM_{2.5}$ derived concentrations from NOAA GOES GWR. The 25th and 75th percentiles are shaded for *Smoke-free* and EK_{all}. The derived $PM_{2.5}$ concentrations at 7:00 and 19:00 have been removed due a limited number of observations in comparison to the other hours with data (70 observations at 7:00 and 142 at 19:00 compared to a mean number of observations of 299).

Chapter 4

CONCLUSIONS AND FUTURE WORK

4.1 CONCLUSIONS

In this study, we deployed 38 PurpleAir monitors in the Flint Hills region of Kansas to study the impact of smoke from prescribed burning during the spring burning season (March through May) 2022. The burning season was impacted by smoke transported from outside of the region in addition to the smoke from the local prescribed fires. To investigate the impact of local fires alone, we separated transported smoke from eastern Kansas smoke using a decision-tree. We compared our in situ measurements and two satellite products (NOAA GOES GWR and the V5GL03 Monthly Hybrid $PM_{2.5}$).

Median $PM_{2.5}$ concentration on *Smoke-free* days during spring 2022 was 4.0 μg m^{-3}, in comparison to 9.4 μg m^{-3} for any day with smoke originating in eastern Kansas (EK_{all}). $PM_{2.5}$ concentrations were highest in the Flint Hills counties and directly to the east in 2022 compared to other areas of eastern Kansas. The diurnal cycle of $PM_{2.5}$ on days impacted by smoke from local fires (increasing in the evening time) was also most pronounced in the FH region.

Hourly $PM_{2.5}$ concentrations during the day from the NOAA GOES GWR product were similar to our ground-based measurements on smoke-free days and days with local fires. During days with local fires, there was an overnight peak in $PM_{2.5}$ observed with in situ measurements and unobserved by the satellite product, thus, satellite products underestimate $PM_{2.5}$ in the Flint Hills. We found higher concentrations of $PM_{2.5}$ in the FH area compared to the surrounding areas during the 2022 burning season (March-May).

Transported smoke introduced uncertainty in our attribution of $PM_{2.5}$ to smoke. We separated and designated smoke using a decision-tree. We were motivated to create our own decision-making process to reduce bias from the satellites when there were limited observations (e.g, cloudy days, overnight). With this process, we may have introduced our own bias. For example, on days when there were no satellite observations and the ground-based $PM_{2.5}$ concentrations were low, we likely designated this as a *Smoke-free* day. If there had been transported smoke aloft during this type of day, we could have overestimated the smoke impact. Further, due to the low number of days with only local smoke, we included days with both transported and local smoke to our estimates of local-smoke $PM_{2.5}$, adding uncertainty to our estimates.

Our results indicate that smoke from small, short-lived, prescribed burns increase ground-based $PM_{2.5}$ concentrations. Smoke and the associated health effects from prescribed fires should be further investigated in the Flint Hills and other areas of the US. Rural communities are often most affected by prescribed burning, but these regions often lack consistent long-term federal air quality monitors. The health effects of smoke from prescribed burns are also understudied. Satellite derived products give estimates of ground-based concentrations in these areas, but in the Flint Hills, there is an increase of smoke from daytime prescribed fires overnight, when satellite observations are limited. To further investigate the impact of smoke in the Flint Hills and the effect of health, future work could develop a product of smoke estimates using fused methods. These smoke estimates could be applied to health data to assess the impact.

4.2 FUTURE WORK

The 2022 springtime burning season in the Flint Hills was significantly impacted by transported smoke. The presence of transported smoke made our attribution of $PM_{2.5}$ to local fires in eastern Kansas more challenging and added uncertainty to our estimates of the local-smoke contribution to $PM_{2.5}$. To further investigate smoke from prescribed fires in eastern Kansas and to investigate the interannual variability of burning, a similar field campaign and analysis could be conducted for another burning season. During a year with less smoke transport, our decision-making process would be simpler, as the only smoke designations would be smoke-free and local-smoke impacted, and the local-smoke contribution to $PM_{2.5}$ could be more easily and consistently isolated.

Other future work could include developing a gridded smoke estimate fusion product. To calculate smoke estimates, we would interpolate in situ measurements from EPA AQS and PurpleAir using ordinary kriging (Janssen et al., 2008). We would use the relationship between GOES-16 ABI AOD and our continuous interpolated ground-based $PM_{2.5}$ to derive $PM_{2.5}$. The smoke product would include daily maps for local-smoke impacted days and days without smoke. This type of product would be possible if our field campaign was relaunched for another year of study. The 2022 burning season would be difficult to make smoke estimates for due to transported smoke. If our campaign was done in future years, we could improve on our deployment by expanding the coverage of PurpleAir to allow for easier interpolation. The development of this smoke product would be highly useful for comparing current $PM_{2.5}$ derived products (e.g., NOAA GOES GWR and the V5GL03 Monthly Hybrid $PM_{2.5}$), which do not currently use measurements from low-cost sensor networks, like PurpleAir. We would also be able to better evaluate the significance of our deployment of PurpleAir by comparing smoke estimates with and without the PurpleAir we deployed. Additionally, these smoke estimates could be used alongside health data in Kansas (e.g., emergency department visits for asthma morbidity) to assess the impact of prescribed fires in Kansas to health.

Additionally, we could investigate prescribed fires in another region. Prescribed burns account for 1.4 million burned acres annually in Georgia (Commission, 2019). The $PM_{2.5}$ emissions from prescribed fires in Georgia in 2020 were comparable to those in Kansas (Figure 4.1). With Georgia having 20 regulatory monitors, mostly in urban areas, low-cost monitors could be deployed to fill in gaps in the current monitors. Quantifying $PM_{2.5}$ concentrations in Georgia would be distinct from our Kansas campaign because of different fuel types (forest versus tallgrass) (Brey et al., 2018) as well as different meteorological conditions (e.g., humidity, temperature).

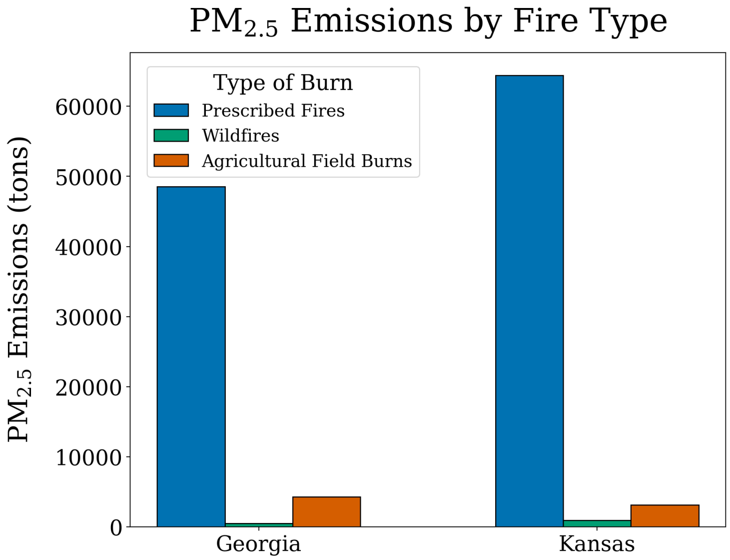

Figure 4.1: PM$_{2.5}$ emissions by fire type from the EPA National Emissions Inventory (NEI) 2020 (US EPA, 2023).

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Appendix A

ADDITIONAL FIGURES

A.1 KANSAS POPULATION

The Flint Hills counties in Kansas are sparsely populated (Figure A.1). Woodson County was the most populated in 2022 compared to the other Flint Hills counties, with about 71,000 people. The most populated county in Kansas in 2022 was Wyandotte county, which includes part of the Kansas City metropolitan area. This county included over 600,000 people, more than 8 times the population of Woodson county.

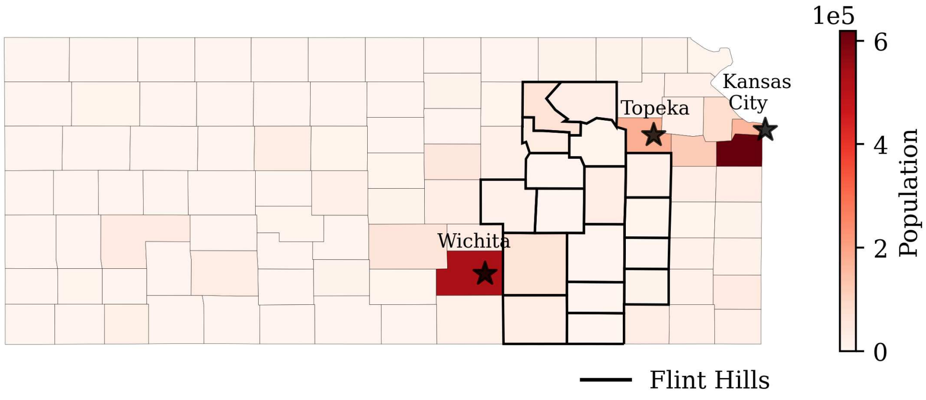

Figure A.1: The 2022 population by county, with the Kansas Flint Hills counties outlined (Bureau, 2023).

A.2 PURPLEAIR PRE-DEPLOYMENT QUALITY CHECK

Prior to deploying our PurpleAir monitors to the field, we conducted a quality check of the monitor performance. We installed 44 PurpleAir monitors in Fort Collins, CO. We ran three separate tests to evaluate the sensors. The first group of 19 sensors were evaluated from 28 October 2021 to 04 November 2021. The second group of 19 sensors were evaluated from 11 November 2021 to 18 November 2021. The last group of 8 sensors were evaluated from 20 November 2021 to 01

December 2021. One PurpleAir sensor remained up for the entirety of the testing. We compared the $PM_{2.5}$ concentrations from channel A and channel B of the PurpleAir (Figure A.2). The average $PM_{2.5}$ concentration for the first test was 8.14 µg m^{-3}. The average $PM_{2.5}$ concentration for the second test was 2.91 µg m^{-3}. The average $PM_{2.5}$ concentration for the third test was 7.17 µg m^{-3}. The mean correlation between channels for all three testing periods was 0.995.

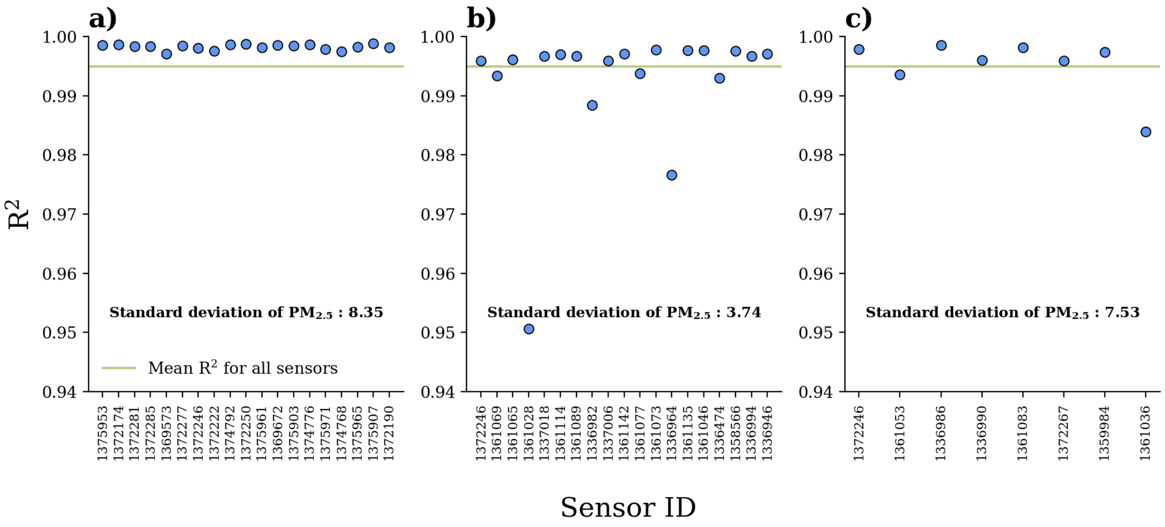

Figure A.2: Pearson correlation between PurpleAir channel A and channel B in comparison to the average correlation of all sensor channels (horizontal green line) for testing period 1 (a), 2 (b), and 3 (c).

Additionally, we compared the $PM_{2.5}$ concentrations from our PurpleAir sensors to a co-located Federal Equivalent Method (GRIMM) monitor. The GRIMM $PM_{2.5}$ concentrations were compared to the PurpleAir for the three testing groups, over the same time periods we compared the PurpleAir channels (Figure A.3). The average correlation for all three tests was 0.68.

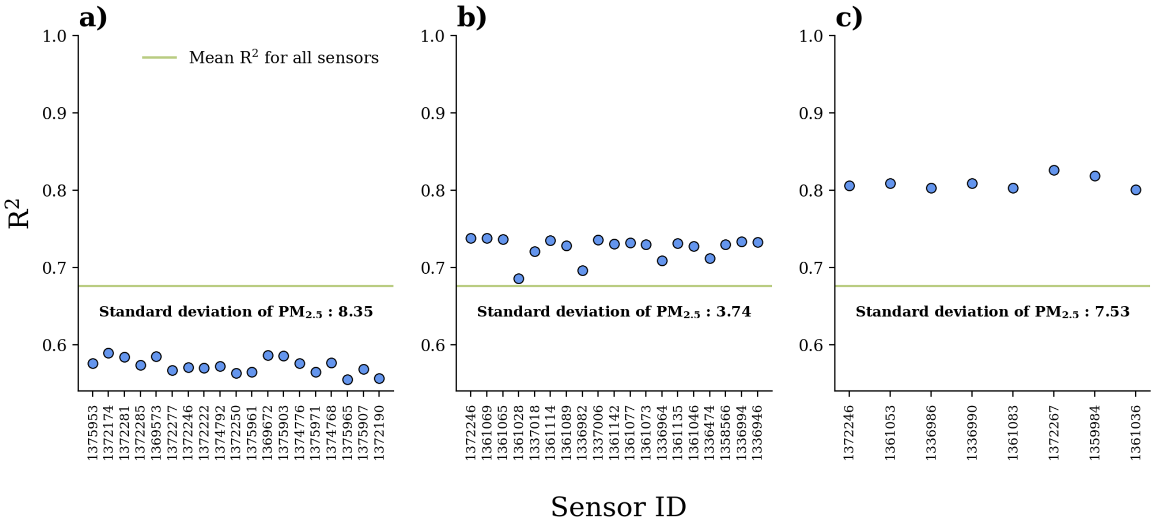

Figure A.3: Pearson correlation between PurpleAir sensors and the GRIMM monitor in comparison to the average correlation of all sensors (horizontal green line) and the GRIMM for testing period 1 (a), 2 (b), and 3 (c).

A.3 GROUPING OF MONITORS FOR SMOKE DESIGNATION

We grouped nearby monitors and categorized the smoke impact of them together (Figure A.4). Monitors in close proximity had a similar smoke impact and could therefore be categorized as one group. Grouped monitors had an average correlation of 0.72.

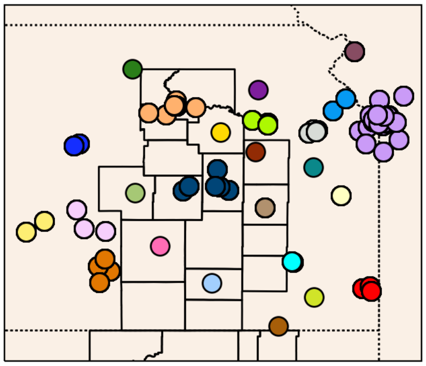

Figure A.4: Grouping of monitors for smoke categorization.

To evaluate our grouping of monitors, we calculated the correlation and mean absolute difference between the $PM_{2.5}$ concentration from each monitor in a group (Figure A.5). The grouped monitors had a higher median correlation and a lower median absolute difference during the campaign. There were three monitors with a correlation < 0.4. These three monitors were located in the Kansas City area, and we expect there to be more variability in $PM_{2.5}$ concentrations in urban areas.

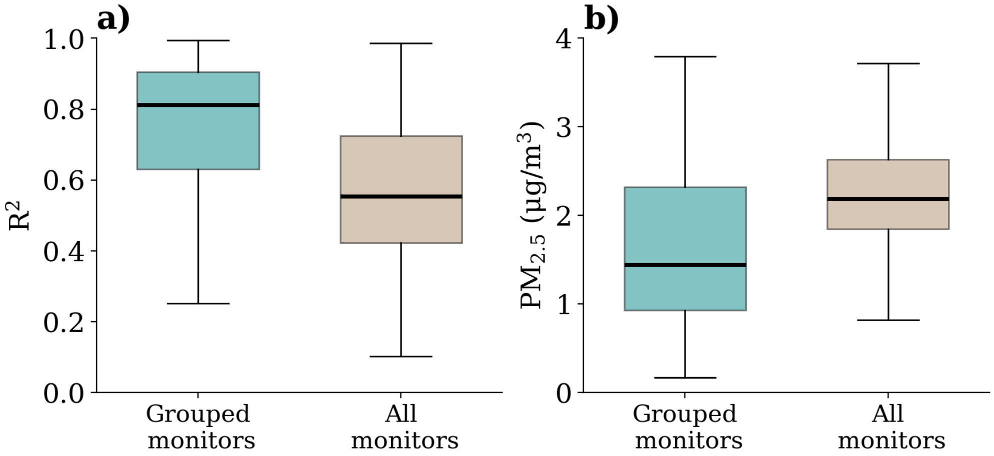

Figure A.5: Correlation a) and mean absolute difference b) for the grouped monitors (blue) in comparison to the statistics for all of the monitors (beige).

A.4 SMOKE DESIGNATION DECISION TREE

The first factor in the decision-making process was the presence of HMS smoke plumes (Figure A.6). Although the HMS product may not capture all smoke (i.e., on overcast days or at night), we found it to be the best indicator of the presence of smoke in eastern Kansas. If HMS smoke plumes were localized over the monitor (with a buffer distance), we then determined if there were HMS fire hotspots nearby and to the west of the monitor(s). if there were no fires upwind, then we designated the daily measurement as *Smoke-free* for the day. If fires were present, then we used the monitor(s) $PM_{2.5}$ concentration(s) (day and/or nighttime). If concentrations were elevated (> 10 µg m^{-3}), we designated this as an EK_{only} day. If the monitor $PM_{2.5}$ concentration was not elevated (< 10 µg m^{-3}), this was designated as a *Smoke-free* day.

On days with HMS smoke plumes over the monitor(s), we determined if the overlapping smoke plume(s) originated from outside eastern Kansas or the FH counties in northern Oklahoma. If the plumes were from within eastern Kansas and the monitor $PM_{2.5}$ concentration (day and/or nighttime) was > 10 µg m^{-3}, we designated this as an *EK*$_{only}$ day. If the $PM_{2.5}$ concentration was < 10 µg m^{-3}, we assigned this as a *Smoke-free* day. If the HMS smoke plumes originated from outside of eastern Kansas or the northern Oklahoma FH counties and there were also smoke plumes originating from within eastern Kansas or northern Oklahoma, we considered this to be an *EK+T* monitoring day. If no local plumes were detected, but there were HMS fire hotspots within 75 km of the monitor(s), we designated this as a *Transported Smoke Impacted* day. When there were no fire hotspots, we considered the monitor(s) with $PM_{2.5}$ concentrations > 10 µg m^{-3} as an *EK+T* monitoring day and the monitors(s) with $PM_{2.5}$ concentrations < 10 µg m^{-3} to be a *Transported Smoke* day.

The HMS product does not capture every smoke plume, thus, for days with no overlapping smoke plumes, we relied on several other data sources. If $PM_{2.5}$ concentrations were low (<10 µg m^{-3}) or high concentrations were centered on an urban area (Kansas City, Wichita, or Topeka), then these were designated as *Smoke-free* days. If the concentration was elevated (>10 µg m^{-3}) at an isolated location and there were nearby hotpots, this was designated as *EK*$_{only}$.

If $PM_{2.5}$ concentrations were elevated across the region, we used coarse PM concentrations from the 9 EPA AQS monitors in the region and observations from the Kansas Automated Surface Observing System in Emporia, KS (EMP) to determine if it was a dust-impacted day. When coarse PM concentrations were >25% than the 2022 seasonal average for each individual monitor, the measurement was designated as impacted by dust and *Smoke-free*.

If $PM_{2.5}$ concentrations were elevated across the region, but not coarse PM concentrations, we designated as *Transported Smoke Impacted* if there was clear transported smoke in the previous day of monitoring. If there were also fire hotspots in the region, we designated these measurements as *EK+T*. For these days without HMS plumes, we additionally used AOD and True-Color imagery from GOES to better inform our decision-making. We used daily averages of AOD

(Zhang et al., 2020) and multi-step animation of AOD images from NOAA NESDIS AerosolWatch (https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/). We also viewed animations of GeoColor from AerosolWatch.

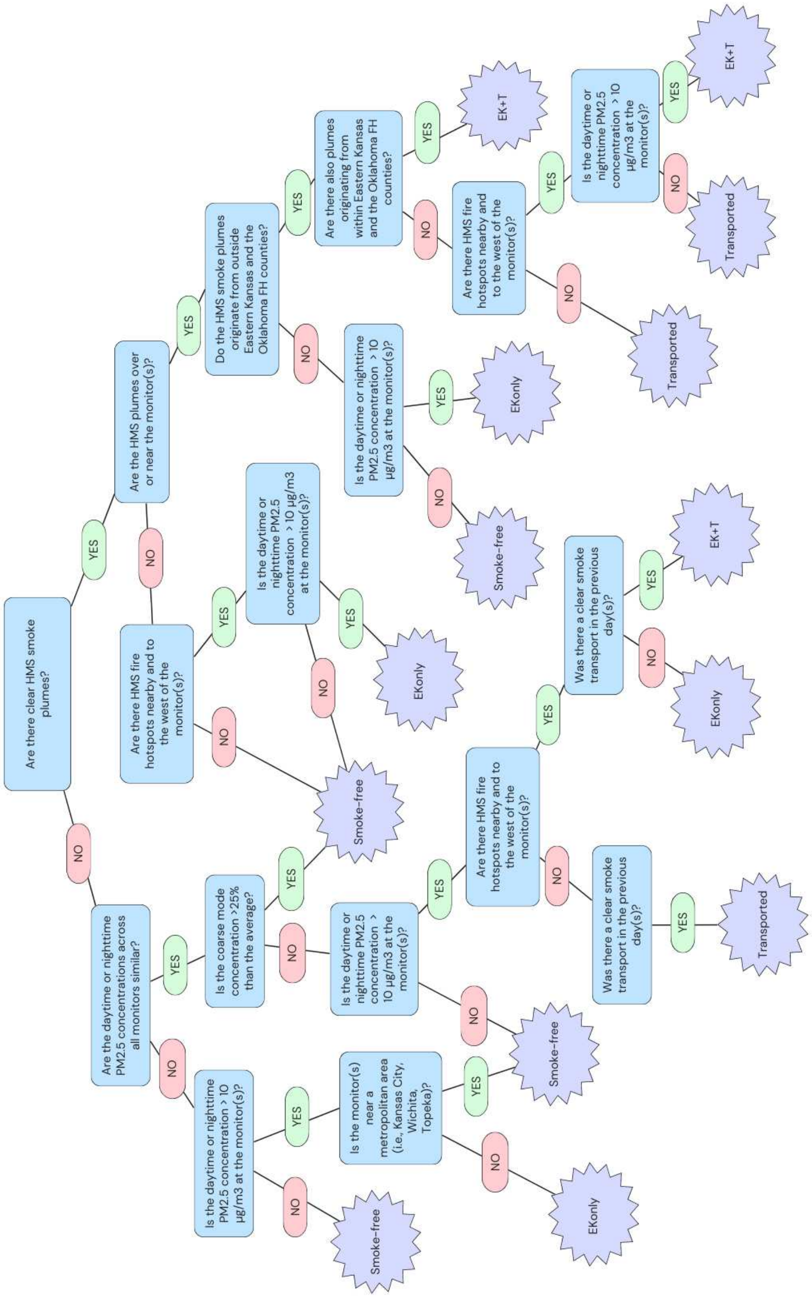

Figure A.6: Decision tree for categorization of smoke.

A.5 SMOKE TRANSPORTED FROM NEW MEXICO

During our field campaign, New Mexico experienced two of the state's largest wildfires in history (Calf Canyon/Hermits Peak). The wildfires and our campaign overlapped from 6 April to 31 May 2022. This event transported a considerable amount of smoke to eastern Kansas. For example, on 23 April 2022, there were no local fire hotspots identified by HMS in eastern Kansas; however, there were smoke plumes over the area (Figure A.7). There are many fire hotspots in northern New Mexico, which likely was the source of this smoke.

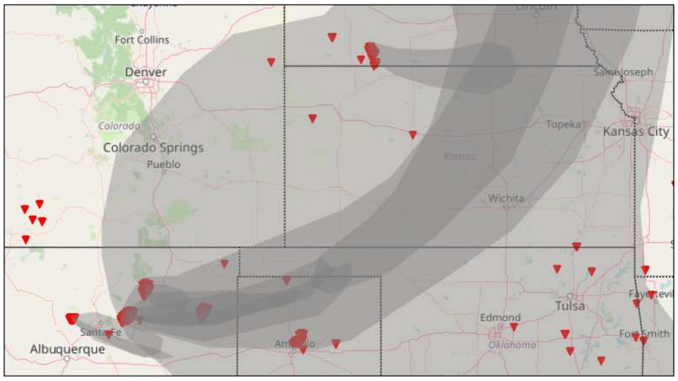

Figure A.7: HMS smoke plumes and fire hotspots for 23 April 2022 during the Calf Canyon/Hermits Peak wildfire in New Mexico.

The Calf Canyon/Hermits Peak wildfires persisted for months and overlapped with our campaign for 55 days. Figure A.8 shows the percentage of these days where there were HMS smoke plumes over the mapped area. New Mexico (including eastern Kansas) experienced a high percentage of days with smoke overhead.

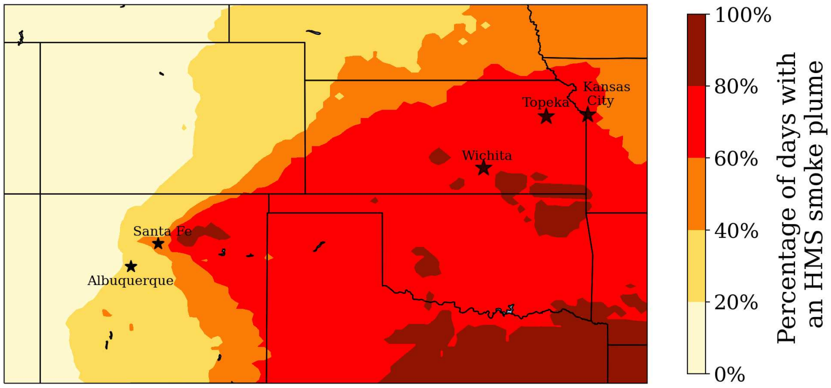

Figure A.8: Percentage of days with an HMS smoke plume during the Hermit's Peak/Calf Canyon New Mexico wildfire and our campaign (6 April to 31 May 2022).

A.6 COMPARISON OF SATELLITE PRODUCTS

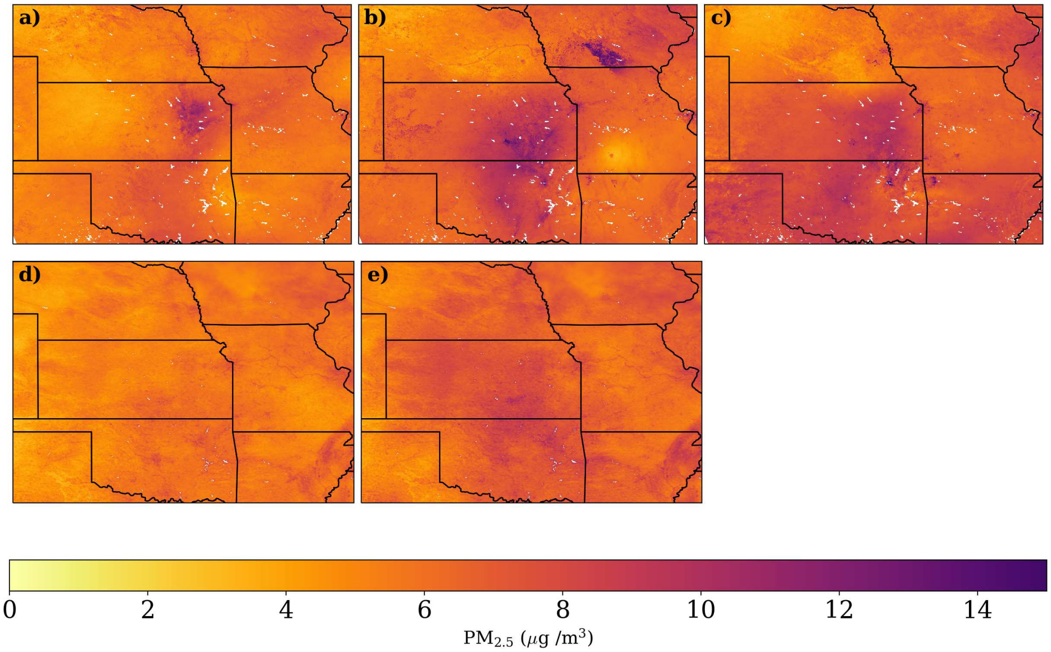

Figure A.9: Supplementary Figure 9: Comparison of seasonal averages (March - May) of the NOAA GOES PM$_{2.5}$ product for 2020 (a), 2021 (b), and 2022 (c) and the V5GL03 Monthly Hybrid PM$_{2.5}$ product for 2020 (d) and 2021 (e).