ACUTE ATMOSPHERIC PM 2.5 EXPOSURE IN MONTANA:

HUMAN HEALTH RISK AND

ANALYSIS OF RELATED RISK COMMUNICATION MEASURES

by

Bethany Jo MacCarter

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DEDICATION

I would like to dedicate this paper to my former IB Environmental Systems and Societies students from Shanghai American School. Your thoughtful discussions and enthusiasm for learning (even in the midst of a pandemic) furthered my passion for Environmental Science, which inspired me to pursue this master's degree.

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LIST OF ABBREVIATIONS

Abbreviation	Full Terminology
AQI	Air Quality Index
CAA	Clean Air Act
EPA	Environmental Protection Agency
EC	Elemental Carbon
ED	Emergency Department
ICD10	International Classification of Diseases, 10th Edition
MTDEQ	Montana Department of Environmental Quality
NAAQS	National Ambient Air Quality Standards
NOAA	National Oceanic and Atmospheric Administration
km	kilometers
PM 2.5	Particulate Matter with a size of 2.5 microns or smaller
ppb	parts per billion
SQL	Structured Query Language
VOC	Volatile Organic Compound
WHO	World Health Organization
µg/m3	micrograms per meters cubed

ABSTRACT

Particulate matter with a size of 2.5 microns or smaller (PM 2.5) is an atmospheric pollutant monitored by the Environmental Protection Agency (EPA) and the Montana Department of Environmental Quality. Once inhaled, PM 2.5 results in oxidative stress and inflammation that negatively impacts health, especially to respiratory and cardiovascular systems. Wildfires are a known source of PM 2.5 and since Montana is a state prone to wildfires, I assessed acute PM 2.5 exposure risk to Montanans using sensor data from 15 counties (8 western and 7 eastern) from 2017-2021. Statewide averages revealed acute PM 2.5 exposure risk, and a recurrence of exposure. The average 98th percentile PM 2.5 concentrations and percentage of days above acute thresholds were greater for western counties, and statewide this data positively correlated with wildfire acres burned in a year. Acute exposures typically occurred within fire season for eastern counties, but extended beyond fire season for many western counties, indicating exposure from sources other than wildfires. Using records from a Yellowstone County hospital for 2021, I grouped emergency admissions by PM 2.5 concentrations and found significantly higher admissions when concentrations were above acute thresholds, and a positive linear relationship between PM 2.5 and emergency admissions. I compared Montana with the top 10 states for wildfire in 2021, and found it ranked third in wildfire acres burned, but last in the ratio of PM 2.5 sensors per acres burned. I estimated 79% of Montanans live in a county with a PM 2.5 sensor, but that there are spatially fewer sensors in western Montana. I analyzed data from three Missoula County sensors and found greater differences in Air quality index (AQI) values with increasing distance between sensors and that AQI values differed more during the wildfire than other times of the year. Wildfires are predicted to increase with climate change and to properly communicate PM 2.5 exposure risk and retrospectively analyze health outcomes specific for Montanans, more PM 2.5 sensors should be placed throughout the state.

INTRODUCTION

Air Quality in the United States:

There is a strong consensus in the scientific community that air pollutants impact human health. One of the outcomes of the Clean Air Act (CAA) of 1970 required that the Environmental Protection Agency (EPA) set National Ambient Air Quality Standards (NAAQS) with the goal of protecting human health with an adequate margin of safety (Lattanzio 2022). Furthermore, the CAA requires that scientific evidence be reviewed every five years and standards revised based on updated findings as needed (Lattanzio 2022). Monitoring against standards allows the government to identify non-attainment areas –locations that have pollutant levels exceeding standards– and develop interventions for pollution reduction and attainment of standards. NAAQS have been established for six air pollutants: carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), lead (Pb), and particulate matter, which refers to any inhalable solid or liquid particle found in the air (US EPA 2016). Particulate matter (PM) is further broken down by size as either pollutants with a diameter less than 10 microns (PM10), such as pollen, dust or mold, or pollutants with a diameter less than 2.5 microns (PM 2.5), such as metals, and elemental or organic compounds (US EPA 2016).

In the United States, air pollutants are monitored through location specific air sensors and health risks for the concentration of pollutants are communicated to the public through an air quality index (Table 1). Scientific research on pollutants reviewed for NAAQS is used to determine cutoff values for each AQI category for each given pollutant (Table 1). While NAAQS can be revised, The AQI categories and their corresponding values remain the same to

Table 1: Air Quality Index and PM 2.5 Exposure Risk as Established by the U.S. EPA.
Table revised based on graphics from (Du and Varde 2016)

AQI Category	AQI Index Values	PM 2.5 Breakpoints ($\mu g/m^3$, 24-hour average)
Good	0-50	0.0-12.0
Moderate	51-100	12.1-35.4
Unhealthy for Sensitive Groups	101-150	35.5-55.4
Unhealthy	151-200	55.5-150.4
Very Unhealthy	201-300	150.5-250.4
Hazardous	301-500	250.5-500

maintain consistency in their message and communication of risk to the public. To report a daily AQI value, raw measurements of each monitored air pollutant are converted to a standard AQI value on a scale of 0 to 500. The AQI pollutant that is highest is communicated as the daily AQI for that location (US EPA 2014). For example, if a PM 2.5 daily average of 36$\mu g/m^3$ equates to a standard AQI value of 102 and the ozone daily value was 50 ppb, equating to a standard AQI value of 46, then assuming PM 2.5 was the highest of all other monitored pollutants, 102 would be reported as the AQI value, and this would indicate that the air is "Unhealthy for Sensitive Groups" (Table 1). The public can easily access Daily AQI values online, and some organizations, such as schools, will use these to set guidelines for outdoor activities.

Air Quality in Montana:

Metropolitan areas that have a census-defined population of 350,000 or more are legally required to monitor and report a daily AQI value; however, many other locations monitor and report a daily AQI as well (Code of Federal Regulations 2021). Billings is the largest metropolitan area in Montana, with an estimated population size of 161,300 (US Census Bureau 2019). As such, there are no areas that are legally required to monitor and report daily AQI values. Nonetheless, in 2021, EPA data revealed Montana to have approximately 29 air quality sensors. The Montana Department of Environment Quality (MTDEQ) uses EPA approved sensors to monitor particulate matter within the state (most sensors do not monitor other pollutants). The data from these sensors are used to communicate air quality risks through MTDEQ's website: Today's Air, and this information can also be found on the EPA's website, Nowcast (Montana Department of Environmental Quality 2017).

Air pollutants can originate from various sources which include industry, residential sources, vehicular traffic, dust, and fires. Some physical factors that impact air quality include geography, wind, temperature, sunlight, and human activity. Montana is geographically diverse. The Rocky Mountain range runs through the western part of the state and results in the formation of valleys where air pollutants can easily be trapped, increasing the duration of exposure. Eastern Montana is characterized by plains where wind can disperse air pollutants more quickly. Since Montana is a relatively rural state, urban air pollution from traffic is not of major concern; however, the surrounding nature and forests provide fuel for wildfire, which in combination with climate change and drought conditions makes wildfire a growing concern for Montana. Wildfires tend to occur in the summer months when there is also more sunlight. Increased UV radiation from sunlight increases ozone formation (Adams et al. 2021). In Montana, wildfires and temperature inversions are considered exceptional events that impact air quality but cannot reasonably be prevented or controlled. In a temperature inversion, atmospheric layers exist in which temperature increases with altitude (cooler temperatures at the surface), the opposite of what typically occurs (Rendón et al. 2015). Warmer temperatures have a greater density of particles and a higher air pressure, since air particles move from areas of high pressure to low pressure, the warmer temperatures trap particles in cooler layers at the surface. If air pollutants are present or increasing at the surface, they will be trapped until the inversion layer is broken up. Temperature inversions are a phenomenon typically associated with deep valleys (western Montana) and more commonly occur in the winter. The MTDEQ documents all exceptional events and must report this to the EPA. Documentation of an exceptional event can result in the data being excluded when determining a location's compliance with NAAQS. The MT DEQ has stated that wildfires are the most common exceptional event in the state (Montana Department of Environmental Quality 2017). Based on a report from the Montana Climate Assessment, there is high agreement and robust evidence for the prediction that climate change will result in more fires in Montana, which include increases in the area burned, the number of fires and fire severity (plant mortality). This is the result of increasing temperatures that lead to a longer duration of fire season in conjunction with an increase of fuel from previous efforts of fire suppression (Whitlock et al. 2017). Assuming other sources of pollutants will remain relatively stable, wildfires are one factor that could result in an increase of air pollutants.

Wildfires, Air Pollutants, and Human Health:

Wildfires contribute to air pollution as they emit both fine particulate matter and volatile organic compounds (VOCs). Atmospheric PM 2.5 is small enough to be inhaled and transferred to the cardiovascular system through gas exchange; this particle size can also cross the placental-barrier and blood-brain barrier (Adams et al. 2021). Health impacts from increased particulate matter range from complications to the respiratory and cardiovascular systems to preterm births and neurological impacts, including increased risk for dementia (Adams et al. 2021). Volatile organic compounds refer to substances that exist in the gas-phase, thus making them easy to inhale, upon heating. They include polyaromatic hydrocarbons (PAHs), carbon monoxide, nitrous oxide, aldehydes, benzene, toluene, and others, which can depend on the specific location of the burn (Adams et al. 2021). In the presence of heat and sunlight, nitrous oxide and VOCs can form ground-level ozone as a secondary pollutant. Elevated levels of ozone pollution have been associated with increased complications for asthma and preterm births (Adams et al. 2021). While all pollutants released from wildfires can compromise human health, the scope of this paper will be PM 2.5, a pollutant regularly monitored throughout Montana.

Objectives:

Given this background, the objectives of my research were to: assess human health risk from acute PM 2.5 exposure in Montana (2017-2021), and determine if repeated exposure above the acute threshold could result in exceeding the threshold for chronic exposure (Chapter 1); analyze patterns between acute risk from PM 2.5 exposure and wildfires (Chapter 1); analyze the impacts of PM 2.5 on hospital admissions and respiratory and cardiovascular diagnoses within one Montanan hospital system (Chapter 2); and characterize risk communication within Montana based on analysis of air sensor locations, population size, and geography (Chapter 3).

CHAPTER 1: HUMAN HEALTH RISK ASSESSMENT FOR ACUTE PM 2.5 EXPOSURE TO MONTANANS (2017-2021)

Problem Formulation:

In this risk assessment, I focused on estimating the health risk to Montanans from acute exposure of PM 2.5. I assessed risk based on 15 Montana counties that recorded daily PM 2.5 values from the years 2017-2021. This time span of five years represents years of both high (2017 and 2021) and low (2019) severity of wildfires (Appendix A). Furthermore, of the 15 counties, these can be divided geographically with eight counties in the western region of the state characterized by the Rocky Mountains, and seven counties in the eastern region of the state that are characterized as grasslands or plains. I assessed acute risk by comparing the 98th percentile PM 2.5 from each year to two values established as the 24-hour exposure limit for PM 2.5, one from the U.S. Environmental Protection Agency (EPA), and one from the World Health Organization (WHO). While my focus for this assessment was on acute risk, to assess the relationship that repeated acute exposure has on chronic risk, I also determined the percentage of days in a year that an acute threshold was exceeded and compared the annual mean PM 2.5 to endpoints that the WHO and EPA use to assess chronic risk. While a direct cause of PM 2.5 exposure from wildfires cannot be established for each PM 2.5 value, I determined the date ranges where acute exposure occurred to determine if exposure occurred in fire season only.

Hazard Identification:

Exposure Pathway:

The primary hazard of interest are pollutants with a size less than or equal to 2.5 microns (PM 2.5). While the components of particulate matter are diverse in their chemical composition, all have in common a physical characteristic of being smaller than 2.5 microns. This classification is also the foundation of its hazard as this size allows for the particles to be transported from the alveoli of the respiratory system and to capillaries of the cardiovascular system through gas exchange (Xing et al. 2016). Once in circulation, PM 2.5 can be transported to other systems of the body. Tissue damage and disease is the result of oxidative stress and inflammation which is triggered by the presence of PM 2.5 (Gangwar et al. 2020), (Figure 1).

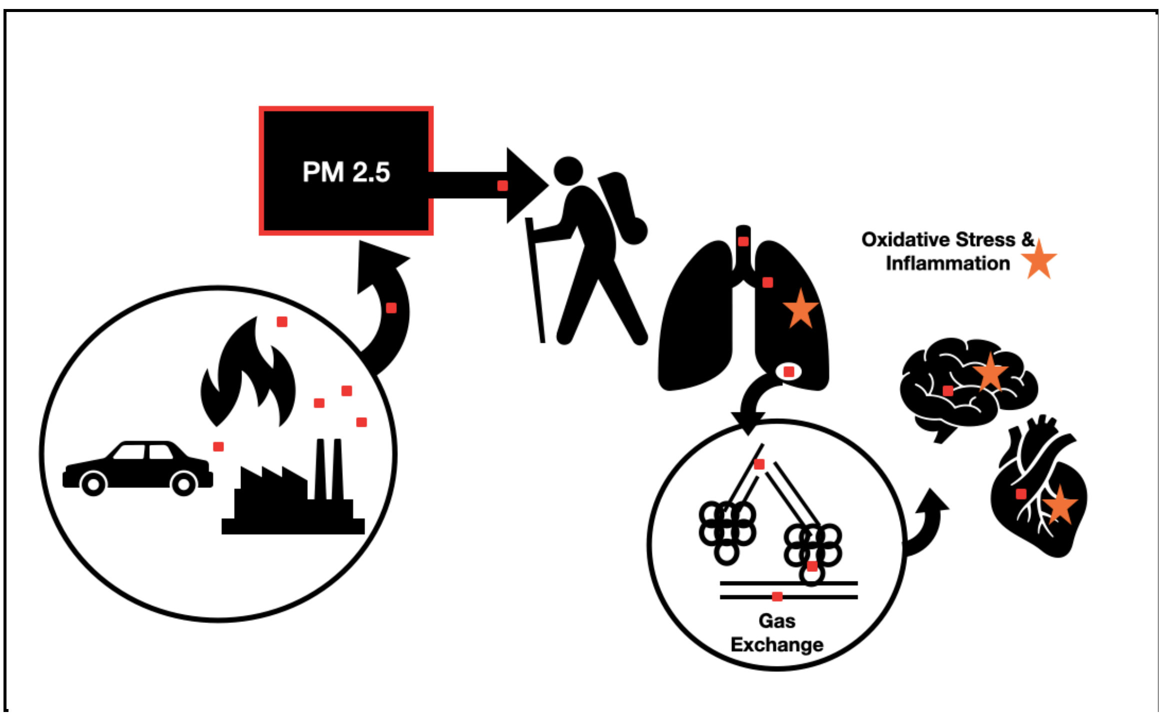

Figure 1: PM 2.5 Exposure Model (Author's diagram); *Sources of PM 2.5 can include vehicles, industry and wildfires, which emit PM 2.5 that humans can inhale from the atmosphere. Once in alveoli of the respiratory system, PM 2.5 can pass to the cardiovascular system via gas exchange and then be transported to all systems of the body.*

Specific impacts and disease states could depend, in part, on the exact composition of the PM 2.5, but several studies have linked PM 2.5 exposure to respiratory and cardiovascular diagnoses (Atkinson et al. 2014).

Components of PM 2.5:

PM 2.5 can be categorized into five groups: elemental or black carbon, organic carbon, nitrate, sulfate, and all remaining particles, which can include metals and ions (US EPA 2002). Studies on PM 2.5 emissions from wildfires reveal the majority of particles (50-75%) are organic carbon, elemental carbon comprises 5-10%, while the remainder is inorganic particles (Jaffe et al., 2020). Elemental carbon, commonly referred to as soot, forms due to incomplete combustion and is composed of graphite-like particles that combine to form larger aggregates. Li et al., (2021) concluded that although elemental carbon comprised only ~8% of the PM 2.5, nearly half of premature deaths were attributed to it. They concluded that health risks may be underestimated when EC is high and overestimated if EC is low although air sensors do not detect these differences (Li et al. 2021). Organic carbon components in wildfires vary, but often include spherical tar balls that increase in size as the plume increases in age (Jaffe et al. 2020). The exact composition and percentage of PM 2.5 species depend on the burn location. For example, grasslands have been found to produce less organic and elemental carbon than shrublands and forests. In addition, a fire near a contamination site would likely increase inorganic metals, while fires located at the wildland-urban interface would likely ignite vehicles, building materials and other fuels that add carcinogens and toxic metals to the air (Jaffe et al. 2020).

Dose-Response Relationships:

PM 2.5 and Human Health:

Most studies investigating the acute impacts of PM 2.5 in humans are retrospective, investigating hospital or mortality data in conjunction with changes in PM 2.5 values in a time series study. A global meta-analysis of 110 time series studies found that a 10 μg/m^3 increase in PM 2.5 results in a 1.04% increased risk of mortality, a 1.51% increase of death due to respiratory disease and a 0.84% increase due to cardiovascular disease (Atkinson et al. 2014). Wei et al. analyzed various disease groups that had shown a known relationship to PM 2.5 exposure in previous studies. They found that for each 1 μg/m^3 increase of PM 2.5 (with a 0–1-day lag), the relative percentage of hospital admissions for these established diseases increased 0.05% to 0.40% each day. Furthermore, when limiting the analysis to days below a threshold of 25 μg/m^3 (the previous 24-hour exposure guideline from the WHO), their findings remained relatively consistent (Wei et al. 2019).

PM 2.5 from Wildfires and Human Health:

Health risks associated with PM 2.5 exposure during times of known wildfires have also been studied. A nationwide study in the United States found that a 10 μg/m^3 increase in PM 2.5 from wildfire smoke was associated with a 2.7% increase of ICU admissions five days later (Sorensen et al. 2021). A nationwide study in Brazil linked a 10 μg/m^3 increase in PM 2.5 from wildfire smoke to a 1.65% increase in all-cause hospital admissions, especially for respiratory (+5.09%) and cardiovascular health (+1.10%) on the day of and after exposure; the effects were most notable for children and the elderly (Ye et al. 2021). A regional retrospective study following the San Diego wildfires of 2007 looked at hospital admissions pre and post wildfire exposure and found that a PM 2.5 classification as "unhealthy for sensitive groups" resulted in a significant increase of emergency admissions for a respiratory condition the day after exposure. Notably, they found that healthcare related to the wildfires persisted beyond the initial wildfire period, extending to times when AQI levels had lowered (Hutchinson et al. 2018). Aguilera et al. (2021) concluded that increases in PM 2.5 attributed to wildfire (when compared to similar non-wildfire PM 2.5 concentrations) resulted in a greater increase of respiratory hospital admissions.

Challenges in Establishing Thresholds for PM 2.5 Exposure:

A challenge for regulation of PM 2.5 is that dose-response studies for this pollutant have been unable to establish thresholds (Tran et al. 2019). Without a clear established threshold, regulating organizations have had to analyze the most up-to-date research to set guidelines or standards for what PM 2.5 concentration equates to acute or chronic risk. For the EPA, NAAQS are used to determine non-attainment areas on a three-year average, while the WHO sets general guidelines for health. Both the EPA (in 2006) and WHO (in 2021) have revised their guidelines for 24-hour (acute) and annual mean (chronic) exposure to PM 2.5. Specifically, the updated WHO guidelines were lowered based on the scientific consensus that adverse health impacts have been observed at relatively low concentrations and no threshold for safe exposure has been established to date (Hoffmann et al. 2021). As a result, the WHO lowered its guideline for 24-hour exposure of PM 2.5 from 25 $\mu g/m^3$ to 15 $\mu g/m^3$. They believe that exposures that exceed this level in a 24-hour period will result in adverse health outcomes (World Health Organization

2021). The EPA is required to set NAAQS as outlined in the CAA and periodically review these standards based on up-to-date research and input from the scientific community (US EPA 2014). In 2006, the 24-hour exposure standard for PM 2.5 was lowered from 65 $\mu g/m^3$ to 35 $\mu g/m^3$ (US EPA 2016).

Table 2: Threshold Concentrations Chosen to Assess Acute and Chronic Risk for PM 2.5.
Although one value is a guideline, and one is a standard, these values are collectively referred to as thresholds, even though true thresholds have not been established.

Organization and usage	24-hour exposure threshold (acute)	Annual mean threshold (chronic)
WHO (guideline)	15$\mu g/m^3$	5$\mu g/m^3$
EPA (NAAQS)	35$\mu g/m^3$ (98 quart. 3-year avg.)	12$\mu g/m^3$ (3-year avg.)

<u>The Relationship Between PM 2.5 Concentration and AQI Values Internationally:</u>

It is worth noting that while reported PM 2.5 values are standard and universally understood, AQI values are set by different regulatory entities in countries. Therefore, an AQI value in the US is unlikely to equate to the same PM 2.5 value in another country. AQI values are meant to communicate risk based on the most up-to-date research available. While the air quality index values and their interpretations do not change, the regulating authority can change the associated breakpoints for PM 2.5, which is often the case with new research. For example, the upper limit of "moderate" and lower limit of "Unhealthy for Sensitive Groups" breaks just after 35 $\mu g/m^3$, the 24-hour exposure standard for PM 2.5 (Table 1). The AQI category communicates that any value over 35.4 $\mu g/m^3$ may cause health concerns for sensitive groups, which includes individuals with pre-existing conditions, like children and the elderly. Even though the AQI value is what's communicated to the public, PM 2.5 values should be used when assessing risk as PM 2.5 values have a universal understanding.

Establishing Threshold Values for this Risk Assessment:

While there is no clear research suggesting thresholds between sensitive groups and the general public, it can be assumed that the most sensitive groups will be affected before the general public, who will begin to see effects as the PM 2.5 concentration increases. Since the goal of these guidelines is to protect the most vulnerable individuals, my risk assessment uses the standards provided by the EPA and guidelines provided by the WHO; and I will refer to these as the 'acute exposure thresholds'. Since the acute threshold for the EPA is set at the lower AQI limit as "Unhealthy for Sensitive Groups", and the WHO threshold is much lower than the EPA value, this assessment will follow a conservative approach of assessing risks for the most vulnerable individuals (Table 2).

Exposure Assessment:

I downloaded the daily mean PM 2.5 concentration data for Montana during 2017-2021 from the EPA's website for Outdoor Air Quality Data. I included counties in the analysis if they had a record of PM 2.5 data from 2017-2021, more than 50% of the year's data, and a January start and December end date. Most sensor data reported had at least 75% of the data within a year with two exceptions being Richland County (67%) and Sanders County (50%) both in 2017. Overall, this approach resulted in a total of 15 counties (eight in the western part of the state and seven in the eastern). Using R studio, I grouped exposure data for each county by year and estimated acute and chronic exposure. In line with how the EPA NAAQS are analyzed, I used the 98th percentile PM 2.5 concentration for each year for assessing acute risk. I used R studio to determine this value for each county for each year. To determine if daily acute exposures were frequent or high enough to tip annual averages into criteria for chronic risk, I also determined the annual mean PM 2.5 for each county by year using R studio.

While the EPA NAAQS assess data based on a three-year average, for this assessment I analyzed data on an annual basis only. One of the aims of the NAAQS is regulation and intervention, which are not meant to be triggered for an anomaly, but when patterns of high exposure (three-year basis) have been established. Furthermore, this analysis would not come to the same conclusion as the NAAQS review as they remove data for exceptional events, such as wildfires, when determining if a location is meeting standards. This assessment is not concerned with compliance, but rather the actual health risk, which is likely to be increased from the exposure of exceptional events, namely wildfires. All data from the exposure assessment are provided in the context of the next section, risk characterization.

Risk Characterization:

To estimate risk, I compared the exposure estimates (98th percentile and annual mean PM 2.5 concentration) discussed in the previous section, to the 24-hour (acute) or annual mean (chronic) exposure thresholds from the EPA and WHO (Table 2). I also determined the number of days in each year that the daily PM 2.5 concentration in a county exceeded the EPA or WHO 24-hour exposure threshold. Since some sensors had missing data within a year, and some counties had more than one sensor, I reported this as the percentage of days in a year that the thresholds for acute exposure were exceeded (Table 4). Additionally, to determine if the dates exceeding EPA or WHO thresholds fell within fire season, I used R to subset data for each county from each year that exceeded the WHO or EPA acute threshold and determined the start and end date of the remaining data. According to a Montana DNRC report of the 2017 Wildfire season, the worst on record, the date of the first fire was March 17th and the date of the last fire was December 11th–this likely represents an extreme timeline (Montana DNRC n.d.). According to the Western Fire Chiefs Association (2022), peak season for wildfires in Northern California typically range from June/July through October/November. Given the extreme season for Montana in 2017 and the typical season in a nearby state, I assumed that if a date range for exceedance of the 24-hour exposure threshold fell between June 1 and November 15, that it occurred within fire season and the elevated PM 2.5 concentration was likely due to wildfire (smoke). I categorized Montana counties geographically as western mountain counties or eastern plains, and statewide for further analysis.

Results:

The 98th percentile PM 2.5 values ranged from 13.7 $\mu g/m^3$ (Gallatin in 2019) to 215.0 $\mu g/m^3$ (Missoula in 2017) in the western counties, while values had a narrower range in eastern counties from 10.43 $\mu g/m^3$ (Phillips 2019) to 44.72 $\mu g/m^3$ (Rosebud in 2021). In 2017, the 98th percentile PM 2.5 values showed that all counties exceeded the WHO, and nine counties exceeded the EPA 24-hour exposure threshold; all but one of the western counties (Gallatin) exceeded the EPA threshold, while only two eastern counties (Powder River & Rosebud) exceeded it. In 2018, all counties exceeded the WHO threshold, but only three counties, all in the western part of the state, exceeded the EPA threshold. In 2019, less than half of the counties exceeded the WHO threshold, which included all but one of the western counties (Gallatin), and no county had a 98th percentile PM 2.5 value that exceeded the EPA threshold. In 2020, all but one county (Richland) exceeded the WHO threshold, and half of the counties in western Montana exceeded the EPA threshold. In 2021, all counties exceeded the WHO threshold, and all but two counties (both eastern) exceeded the EPA threshold (Table 3). The average 98th

Table 3: The 98th percentile daily PM 2.5 concentrations (μg/m^3) and Summaries for Each Year from 2017-2021. *Yellow highlighting indicates the value is above the WHO 24-hour threshold of 15μg/m^3, while orange highlighting indicates the value is above the EPA 24-hour threshold of 35μg/m^3.*

Geography	County	98th Percentile PM 2.5 Concentration (μg/m^3)				
		2017	2018	2019	2020	2021
Western Counties	Flathead	44.92	48.16	23.98	37.48	36.94
	Gallatin	27.42	25.28	13.7	34.62	37.86
	Lewis & Clark	53.6	33.96	23.87	26.01	42.7
	Lincoln	48.01	67.29	29.48	43.35	52.16
	Missoula	215	29.84	26.84	38.47	46.24
	Ravalli	72.43	22.84	17.97	34.81	51.24
	Sanders	207.94	43.2	18.51	34.13	73.02
	Silver Bow	45.9	21.4	24.06	37.22	48.79
	Average	**89.4**	**36.5**	**22.3**	**35.76**	**48.62**
	Std.Deviation	76.37	15.68	5.18	4.93	11.39
	% Above WHO	100%	100%	88%	100%	100%
	% Above EPA	88%	38%	0%	50%	100%
Eastern Counties	Cascade	28.01	30.54	13.1	23	43.94
	Fergus	31.63	25.51	10.55	22.51	39.8
	Phillips	28.06	27.34	10.43	26.37	32.39
	Powder River	36.55	26.28	14.04	29.58	37.8
	Richland	26.32	20	10.88	12.37	29.63
	Rosebud	43.14	25.8	13.01	32.61	44.72
	Yellowstone	29.02	27.33	11.67	26.36	37.72
	Average	**31.82**	**26.11**	**11.95**	**24.69**	**38**
	Std. Deviation	6.02	3.17	1.43	6.48	5.56
	% Above WHO	100%	100%	0%	86%	100%
	% Above EPA	29%	0%	0%	0%	71%
Total	**Average**	**62.53**	**31.65**	**17.47**	**30.59**	**43.66**
	Std.Deviation	61.77	12.49	6.54	7.93	10.4
	% Above WHO	100%	100%	47%	93%	100%
	% Above EPA	60%	20%	0%	27%	87%

percentile PM 2.5 concentration for western counties was greater than the WHO threshold for all years and greater than the EPA threshold for every year except 2019. The average 98th percentile PM 2.5 concentration for eastern counties was greater than the WHO threshold for every year but 2019, and only exceeded the EPA threshold in 2021. The five-year average for all western counties exceeded both the WHO and EPA thresholds at 46.52 ± 40.82 $\mu g/m^3$, while the five-year average for all eastern counties only exceeded the WHO threshold at 26.52 ± 9.93 $\mu g/m^3$. The statewide five-year average of 37.18 ± 32.00 $\mu g/m^3$ exceeded both the WHO and EPA thresholds.

. The maximum percentage of days in a year that any western county exceeded an EPA threshold was 11.48% (Ravalli in 2017), while the maximum exceeded in an Eastern County was 4.61% (Rosebud in 2021). On average, the greatest percentage of days exceeding the EPA and WHO thresholds occurred in 2017, closely followed by 2021. The lowest average percentage of days exceeding EPA & WHO thresholds occurred in 2019. The average percentage of days for exceeding a threshold from the EPA or WHO was higher in western counties for all years (Table 4 and Figure 2). The five-year average for the percentage of days that the WHO threshold was exceeded was: 15.42 ± 9.67% for all western counties, 7.39 ± 5.29% for all eastern counties and

Table 4: Percentage of Days in Each Year (2017-2021) the WHO or EPA 24-Hour Exposure Threshold Was Exceeded

	Percentage of daily PM2.5 concentrations exceeding 24-hour threshold (mean +/- s.d.)					
Year	Total EPA	Western EPA	Eastern EPA	Total WHO	Western WHO	Eastern WHO
2017	4.1 +/- 3.6	6.3 +/- 3.8	1.6 +/- 0.8	17.4 +/- 9.8	24.4 +/- 7.6	9.4 +/- 4.1
2018	1.7 +/- 1.7	2.3 +/- 2.2	1.0 +/- 0.5	10.5 +/- 7.5	14.2 +/- 8.7	6.3+/- 2.1
2019	0.1 +/- 0.2	0.2 +/- 0.2	0.1 +/- 0.2	5.8 +/- 7.8	9.8 +/- 9.0	1.1 +/- 0.5
2020	2.1 +/- 1.6	3.3 +/- 1.3	0.8 +/- 0.6	8.9 +/- 7.0	10.8 +/- 8.5	6.6 +/- 4.2
2021	3.7 +/- 1.7	4.5+/- 1.6	2.7+/- 1.3	15.8+/- 7.2	17.8+/- 8.6	13.5+/- 4.7

11.67 ± 8.85% for all counties statewide, while the five year average for the percentage of days the EPA threshold was exceeded was: 3.31 ± 2.93% for all western counties, 1.25 ± 1.14% for all eastern counties, and 2.35 ± 2.49% for all counties statewide.

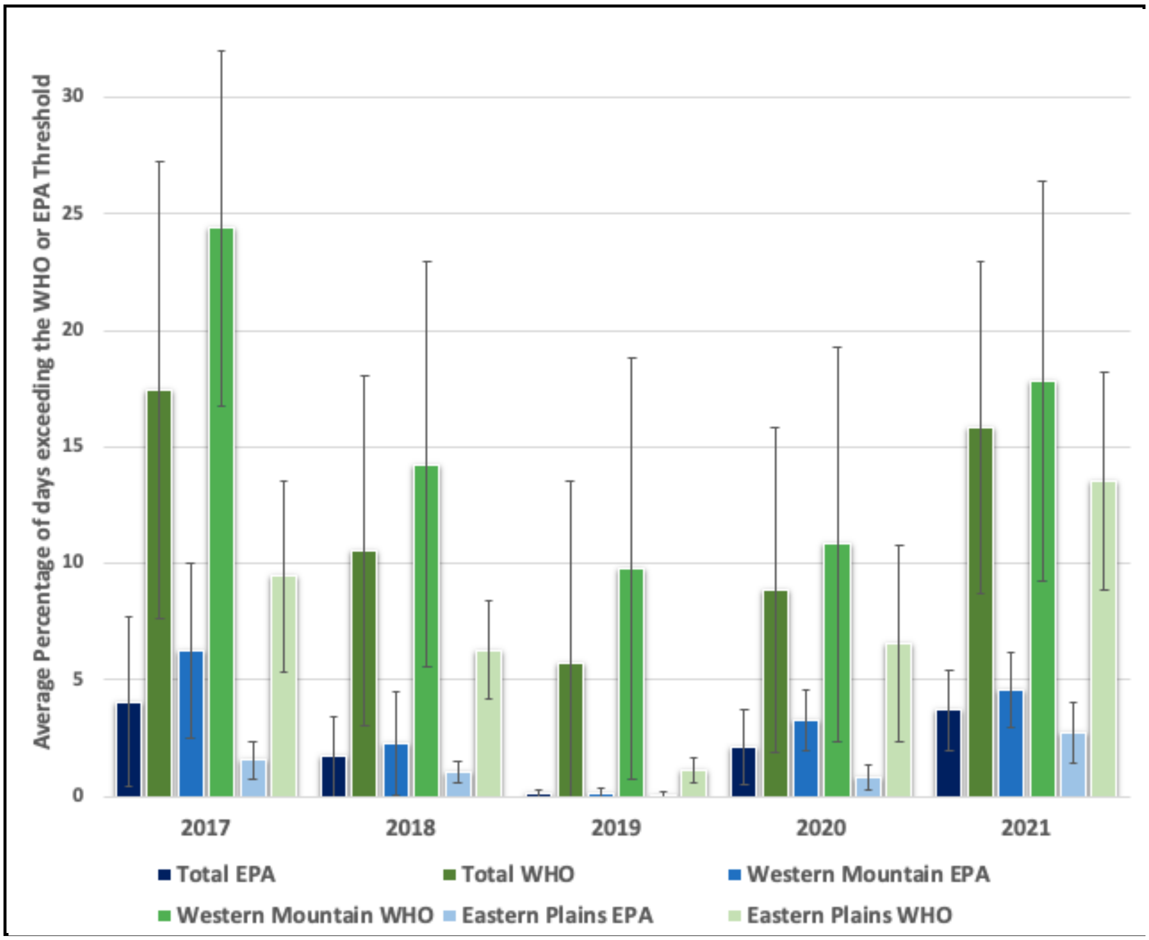

Figure 2: Comparison of the Mean Percentage of Days in which the EPA or WHO Acute Thresholds Were Exceeded in a Year (2017-2021) for All Counties (Total), Western Counties and Eastern Counties.

Annual means were analyzed to determine if acute exposure could lead to chronic risk. In 2017, the annual mean for PM 2.5 exceeded the WHO threshold for all counties, and the EPA threshold was exceeded in five Western counties. In 2018, all counties exceeded the WHO threshold, and only one county (Lincoln) exceeded the EPA threshold. In 2019, nine counties from both eastern and western Montana exceeded the WHO threshold, while no counties exceeded the EPA threshold for chronic exposure. In 2020, all but three counties exceeded the

Table 5: The Annual Mean PM 2.5 Concentrations (µg/m³) and Summaries for Each Year from 2017-2021. *Yellow highlighting indicates the value is above the WHO annual mean threshold of 5 µg/m³; orange highlighting indicates the value is above the EPA annual mean threshold of 12 µg/m³.*

Geography	County	Annual Mean PM 2.5 Concentration (µg/m³)				
		2017	2018	2019	2020	2021
Western Counties	Flathead	10.62	10.17	6.66	6.92	7.84
	Gallatin	5.93	5.39	3.76	4.87	7.86
	Lewis & Clark	9.63	6.42	5.66	5.31	7.57
	Lincoln	14.33	14.56	11.61	13.79	14.62
	Missoula	24.25	9.82	8.82	9.98	11.37
	Ravalli	14.99	6.07	4.61	5.83	9.12
	Sanders	19.78	9.57	6.82	8.57	12.43
	Silver Bow	13.35	5.89	5.66	6.31	9.82
	Average	**14.11**	**8.49**	**6.7**	**7.7**	**10.08**
	Std.Deviation	5.8	3.14	2.5	3	2.54
	% Above WHO	100%	100%	75%	88%	100%
	% Above EPA	63%	13%	0%	13%	25%
Eastern Counties	Cascade	8.35	7.3	5.61	5.66	7.81
	Fergus	5.97	5.3	3.8	4.74	6.61
	Phillips	5.6	5.77	4.05	6.34	6.71
	Powder River	9.68	6.95	5.33	7.57	9.17
	Richland	6.68	5.33	4.49	4.34	6.27
	Rosebud	7.78	5.79	4.3	5.68	9.62
	Yellowstone	7.71	8.44	6	7.05	10.21
	Average	**7.4**	**6.41**	**4.8**	**5.91**	**8.06**
	Std. Deviation	1.42	1.18	0.85	1.17	1.61
	% Above WHO	100%	100%	43%	71%	100%
	% Above EPA	0%	0%	0%	0%	0%
Total	**Average**	**10.98**	**7.52**	**5.81**	**6.86**	**9.14**
	Std.Deviation	5.45	2.59	2.1	2.43	2.33
	% Above WHO	100%	100%	60%	80%	100%
	% Above EPA	33%	7%	0%	7%	13%

WHO threshold, and only one county (Lincoln) exceeded the EPA threshold. In 2021, all counties exceeded the WHO and only two Western counties exceeded the EPA guideline (Table 5). The average annual mean PM 2.5 concentration for all western counties was greater than the WHO threshold for all years, while the average for all eastern counties exceeded the WHO threshold for every year except 2019; neither average exceeded the EPA threshold of 12 $\mu g/m^3$. The five-year average for: all western counties was 9.41 ± 4.31 $\mu g/m^3$, all eastern counties was 6.52 ± 1.66 $\mu g/m^3$, all counties statewide was 8.06 ± 3.63 $\mu g/m^3$. All averages exceed the WHO threshold, but not the EPA threshold.

The first and last date in which an acute threshold was exceeded in a calendar year was assessed to determine the time of the year in which risk occurred. For eastern counties, 100% of

Table 6: Date Range of First and Last Daily PM 2.5 Concentration that Was Elevated Above the EPA 24-hour Threshold Each Year (2017-2021). *Orange highlighting indicates that date range falls within fire season, defined as June 1 to November 15.*

Geography	County	Date Range of PM2.5 Values Exceeding EPA Acute Threshold				
		2017	2018	2019	2020	2021
Western Mountain	Flathead	8/12-9/13	8/8-8/26	2/1	9/12-10/28	7/18-11/3
	Gallatin	9/4	8/15-8/20	N/A	8/20-9/18	8/15-9/9
	Lewis and Clark	8/23-9/9	8/18-8/24	2/12-5/31	9/15-9/18	7/18-9/18
	Lincoln	1/19-9/15	1/7-11/27	8/8-8/8	7/28-10/28	1/1-10/21
	Missoula	1/16-12/11	8/19-8/20	11/2-12/23	9/13-12/08	7/11-12/27
	Ravalli	1/7-9/13	N/A	N/A	8/24-9/19	7/11-9/10
	Sanders	8/9-9/14	4/26-11/4	N/A	9/12-9/19	7/15-9/10
	Silver Bow	1/13-12/12	8/19-8/19	N/A	9/18	2/15-9/18
Eastern Plains	Cascade	8/18-8/31	8/16-8/24	5/31	9/14-9/18	7/16-9/10
	Fergus	8/31-9/13	8/12-8/24	N/A	8/25-9/15	7/16-9/10
	Phillips	7/17-9/12	8/17-8/24	N/A	8/25-8/25	7/24-8/16
	Powder River	6/20-9/14	8/19-8/24	N/A	8/22-10/10	7/26-9/10
	Richland	9/12-9/13	8/18-8/19	N/A	N/A	8/15-10/8
	Rosebud	7/8-9/13	8/19-8/24	N/A	8/22-9/15	7/26-10/6
	Yellowstone	8/28-9/13	7/4-8/19	7/4	7/4-9/18	7/17-9/10
Total	Percentage of Counties with Date Range in Fire Season	73%	86%	33%	93%	73%
West		50%	71%	25%	88%	50%
East		100%	100%	50%	100%	100%

the dates that exceeded the EPA threshold fell within the bounds of fire season for every year except 2019. The full date range spans from as early as May 31 to as late as October 10 in this five-year period. For western counties, the exceedance dates remained within fire season for more than 70% of the counties for every year but 2019. The date range for EPA exceedances vary by western county each year with dates as early as January 1 and as late as December 27 (Table 6).

There was no year in which the dates of WHO exceedance values for each county all occurred during fire season, nor was there a single county whose exceedance values always occurred within fire season. In 2017 and 2021, the two worst fire years on record, no western

Table 7: Date Range of First and Last Daily PM 2.5 Concentration that Was Elevated Above the WHO 24-hour Threshold Each Year (2017-2021). *Orange highlighting indicates that date range falls within fire season, defined as June 1 to November 15.*

Geography	County	Date Range of PM2.5 Values Exceeding WHO Acute Threshold				
		2017	2018	2019	2020	2021
Western Mountain	Flathead	1/4-12/28	1/4-12/10	1/10-12/18	1/19-12/26	1/10-11/20
	Gallatin	8/2-12/31	8/1-9/8	9/5-10/6	8/20-10/27	4/10-12/27
	Lewis and Clark	7/21-12/27	1/5-12/8	7/29-12/9	8/22-10/29	7/18-12/28
	Lincoln	1/1-12/28	1/2-12/26	1/2-12/31	1/1-12/31	1/1-12/31
	Missoula	1/1-12/28	1/1-12/31	1/3-12/31	7/4-12/31	1/1-12/30
	Ravalli	1/1-12/17	1/2-12/17	1/9-11/30	2/21-12/25	7/8-11/22
	Sanders	8/2-11/28	4/24-12/24	1/18-12/3	8/25-12/31	1/29-11/23
	Silver Bow	1/1-12/26	1/8-12/20	1/9-12/27	2/21-12/28	1/10-9/27
Eastern Plains	Cascade	1/8-8/31	7/4-12/2	3/22-8/8	1/17-10/4	2/17-10/5
	Fergus	7/18-9/13	8/2-8/26	5/13-6/1	8/20-10/23	7/11-9/10
	Phillips	7/17-9/13	3/10-8/27	5/31-6/2	7/16-10/10	6/10-10/9
	Powder River	6/6-9/14	6/8-9/13	7/25-10/17	6/10-10/10	4/2-10/9
	Richland	7/17-9/15	3/3-9/2	2/13-6/1	8/25-9/20	1/30-10/9
	Rosebud	5/5-9/14	7/17-8/26	4/5-8/21	8/20-10/10	6/15-10/9
	Yellowstone	1/7-9/13	1/1-9/10	5/31-12/14	1/16-10/10	1/9-12/18
Total	Percentage of Counties with Date Range in Fire Season	27%	27%	13%	54%	20%
West		0%	13%	13%	25%	0%
East		57%	43%	14%	71%	43%

county had exceedance values that fell only within the fire season. The percentage of exceedance events that occurred within fire season was always greater amongst the eastern counties than the western mountain counties (Table 7).

Discussion:

The data from this analysis indicate that Montanans have been exposed to acute levels of PM 2.5 (as defined by both the WHO and EPA) resulting in health risks in both the eastern and western regions of the state, although both concentrations and the percentage of days over the 24-hour exposure thresholds are higher in the western counties. Additionally, these results give an initial indication that risk may be related to wildfire exposure as 2017 and 2021 (the top ranked fire years from this five-year analysis) had the highest 98th percentile PM 2.5 concentrations and percentage of days over the WHO or EPA thresholds, and 2019 (the lowest ranked year) indicated no risk per the EPA guidelines with only western counties experiencing acute exposure risk as indicated by the EPA. If 2019 can be thought of as a control year, it can be assumed that at a baseline, the 98th percentile PM 2.5 exposures in western counties are higher than eastern counties, likely on account of the mountain/ deep valley geography that can trap particulate matter and, under unique meteorological circumstances, lead to temperature inversions. In years when wildfire exposure was highest (2017 and 2021), the 98th percentile PM 2.5 values were highest and resulted in health risk as indicated by the WHO threshold for all counties, and risk as indicated by the EPA threshold for western and some eastern counties. The location of the fires also matters, and although 2017 was the worst wildfire season on record, the percentage of days that exceedance values occurred in eastern counties were higher in 2021. This observation could be the result of the proximity of wildfires to the nearest sensor, which in the eastern region of the state is more spread out (see Chapter 3). Although unconfirmed, it is possible that more wildfires in 2021 occurred near PM 2.5 sensors in eastern counties than in 2017.

Without exceptional events, the annual PM 2.5 should be considered relatively stable from year to year. There will be predictable traffic patterns and sources of pollutants in an area from industry and residential areas; however, the annual means are highest in 2017 and 2021 and lowest in 2019, showing a pattern with wildfire exposure. Again, using 2019 as a control year, annual means are below the threshold in all eastern counties and only exceed the WHO threshold of 5 $\mu g/m^3$ in 75% of western counties; this finding indicates there may be a baseline level of chronic risk in western counties as defined by the WHO, but not at levels defined by the EPA. In years with larger incidences of wildfires, the annual mean increases to levels where all eastern counties are above the WHO threshold and some western counties exceed the EPA threshold; this findings may indicate that an increase of wildfires could result in chronic exposure of PM 2.5 to all Montanans as indicated by the WHO and to western Montanans as indicated by the EPA.

The WHO guideline for 24-hour exposure is very low and as a result may be exceeded by causes that aren't exceptional events. As a result, the percentage of days exceeding a WHO guideline are more likely to fall outside of the range of fire season, especially in western counties; this finding indicates that in western counties, PM 2.5 values often elevate to levels of risk, but that the cause cannot be attributed to wildfires alone. Several dates for exceeding acute thresholds in western counties occur within the winter that could be the result of temperature inversions, or just a general increase in pollutants, possibly from increased energy/heat use, and these pollutants can accumulate within valleys due to western Montana geography. Although other sources of acute PM 2.5 exposure exist in western counties, wildfires are still a contributing source, and the larger percentages of days each year above the acute thresholds correlating with the worst fire years provide support for this. The date ranges for eastern counties indicate that wildfires may be the primary source of elevated PM 2.5 concentrations in this region.

Further Analysis Between PM 2.5 Exposure and Wildfires:

Methodology:

To further analyze the relationship between wildfires and PM 2.5 emissions, I recorded the historical wildland fire statistics for Montana spanning 2017-2021 from the National Interagency Fire Center records: "Historical Fire-end statistics by state" (Appendix, Table A). I performed simple linear regression models using R studio to test the hypothesis that increasing wildfire area burned results in increased PM 2.5 concentrations and thus increases the 98th percentile PM 2.5, the percentage of days above the WHO or EPA acute threshold and the annual mean. Wildland acres burned in a year was used as the explanatory variable and the 98th percentile PM 2.5, annual mean, or percentage of days per year where the EPA or WHO threshold were exceeded were set as response variables. To test the hypothesis that an increase in days with acute PM 2.5 leads to chronic risk, I performed a simple linear regression model using the percentage of days per year above the EPA or WHO guideline as the explanatory variable and the annual mean as the response variable. These models were constructed using the same data set of PM 2.5 discussed in the exposure assessment for the 15 Montana counties. I completed these regressions using data for the whole state, western counties, and eastern counties; however, due to similar trends, I only reported the statewide data in the results section.

Results:

A positive linear relationship between all explanatory and response variables for all models was demonstrated. Collectively, it is predicted that for every additional 10,000 acres burned, there would be a 0.3 µg/m^3 increase in the 98th percentile PM 2.5, a 0.04 µg/m^3 increase in the annual mean PM 2.5, a 0.03% increase in days above the EPA acute threshold, and a 0.08% increase in days above the WHO acute threshold ($p < 0.001$), (Appendix B). A linear regression model also predicts that for each 1% increase in the number of days above the acute EPA threshold, there would be a 1.19 µg/m^3 increase in the annual mean PM 2.5 concentration and for each 1% increase in the number of days above the acute WHO threshold, there would be a 0.37µg/m^3 increase in the annual mean PM 2.5 concentration ($p<0.001$), (Appendix, Table B).

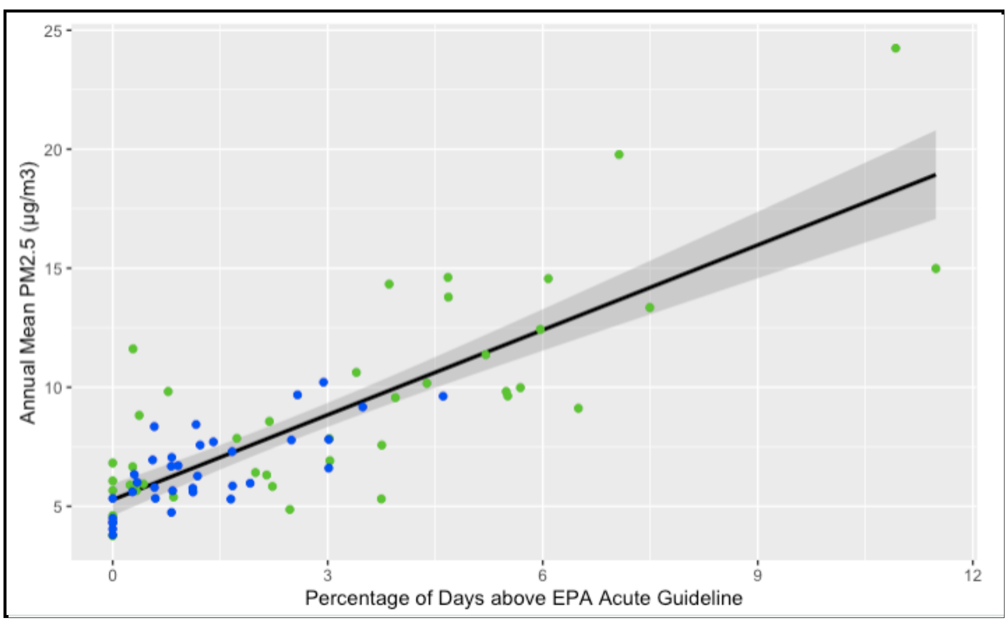

Figure 3: Relationship Between the Percentage of Days Above the EPA 24-hour (acute) Exposure Threshold of 35µg/m^3 and the annual mean PM 2.5 concentration (µg/m^3) Used to Assess Chronic Risk *Green scatter plots represent western counties, blue scatter plots represent eastern counties, and gray shading represents standard error of the regression.*

The regression line allows for a prediction that at approximately 3.5% of days over the WHO threshold (~13 days in a 365-calendar year), the WHO chronic threshold of 5μg/m^3 would be met; many counties from both regions already fit this criterion. At approximately 5.6% of days over the acute EPA threshold (~20 days in a 365-calendar year), the EPA chronic threshold of 12 μg/m^3 would be met (Figure 3). Only western counties exceed 5.6% of days over the EPA acute threshold and thus are most at risk for exceeding the chronic threshold.

Discussion:

The year 2017 was the worst fire year on record in Montana. In that year, for all counties statewide, the average 98th percentile PM 2.5 was 62.53 μg/m^3, the annual mean was 10.98 μg/m^3, the percentage of days above the acute EPA threshold was 4.1%, and the percentage of days above the acute WHO threshold was 17.4%. The 2017 Montana Climate Assessment predicts that under all future climate models, temperatures are expected to rise, and precipitation will increase in the fall/winter/spring but decrease in the summer by mid-/end- of the century. Even with increased precipitation from fall-summer, the effective moisture in the ground is expected to decrease from the rising temperatures, and summers are predicted to be exceptionally dry (Whitlock et al. 2017). Wet springs that result in dense grassland vegetation followed by extremely dry summer conditions often result in classification as "extreme fire danger". The Montana Climate Change and Human Health Assessment predicts that under extreme climate projections, the number of days with extreme fire danger will increase for all Montana counties through the summer; this is not only predicted to increase the length of fire season, but also the severity, as the acres burned will increase as well (Adams et al. 2021). Based on these predictions and the linear regression models, if the area burned by wildfires increased by 100,000 acres, the average statewide 98th percentile would increase to 65.53 µg/m3, the annual mean would increase to 11.38 µg/m^3 (just 0.62 µg/m^3 short of the EPA threshold for chronic risk), and the percentage of days above the acute EPA and WHO thresholds would increase to 4.4% and 18.2%, respectively. Inputting these predictions for percentages above the acute thresholds into the linear regression models, the predicted annual means for percentage of days above a given threshold with an additional 100,000 acres burned were: 10.47 µg/m^3 for the WHO model and 10.51 µg/m^3 for the EPA model. While both values are below the actual annual mean in 2017, this still shows the average annual mean is far above the WHO threshold for chronic exposure and is nearing the EPA threshold of 12 µg/m^3.

Wildfires result in an increase of the 98th percentile PM 2.5 concentration and the percentage of days over the EPA and WHO guidelines, thus increasing the chance of acute risk and the number of occurrences. Increasing the number of days over the WHO or EPA guidelines results in an increase in the annual mean, which increases the likelihood of chronic risk. In sum, increasing wildfires in Montana are predicted to result in an increased 98th percentile PM 2.5 concentration, indicating acute exposure, the frequency of exposure, and the likelihood of classification as chronic exposure.

Nonetheless, these linear regression models have several limitations. First, the regression is based on data for all Montana counties when there is a large range of variation of PM 2.5 concentrations throughout the year, not just between eastern and western counties, but also between counties within a given region. While the relative trends for the highest 98th percentile PM 2.5 concentrations and percentage of days above the acute thresholds follow for most Montana counties each year, the degree of magnitude varies and as a result applying this regression model for the state of Montana will not accurately apply to each individual county and region. Along these lines, the wildfire statistics are summarized for the whole state while there may be occasions when a fire recorded in one region of the state has no or minimal impact on air quality in a separate region of the state. Although wildfire frequency and severity tracks with climate and drought conditions and should adequately serve to correlate the two values, using the statewide data to make predictions of acres burned to PM 2.5 values is likely to be limited in its accuracy. Furthermore, Jaffe et. al (2020) reported that area burned was not well-correlated with PM 2.5 emissions, as emissions depended less on area burned and more on the burning conditions, type of fuel, and density (smoldering fires from dense forests produced greater PM 2.5 than flaming combustion and grasslands). These findings can be thought of as preliminary, showing a need to further investigate these relationships with greater accuracy.

CHAPTER 2: PM 2.5 and EMERGENCY DEPARTMENT ADMISSIONS, YELLOWSTONE COUNTY, 2021

Methodology:

I completed this section of the investigation under the guidance of data scientists from a Montana Hospital. In fulfillment of my internship, I wrote a proposal to investigate the relationship between PM 2.5 concentration and hospital admissions/ diagnostic codes within Yellowstone County in 2021 (a year with known wildfires and AQI levels that reached classification as “unhealthy”). I presented the proposal to the hospital’s institutional review board, which approved the study. Ben Carter (hospital data scientist) wrote and performed a SQL query to obtain hospital records from the shared clinical encounter database within the hospital's server; all patient data were de-identified. Using R studio, I merged patient data with daily PM 2.5 data by date. To determine the impact of PM 2.5 on systemic diagnoses, I filtered data by ICD10 diagnostic codes for all respiratory disorders and all cardiovascular disorders. I used the lead function in R to determine if there was a specific time frame after exposure that had the greatest increase on emergency department (ED) admissions or diagnoses. I grouped ED admission data by days above and below the EPA or WHO acute thresholds and performed a Welch's two sample T-test between the two groups. I performed linear regression to test the hypothesis that increasing PM 2.5 concentrations would result in an increase in hospital admissions where: daily PM 2.5 values were the explanatory variable and ED admissions (all-cause, respiratory, and cardiovascular) over a chosen time range were set as response variables. In addition, I downloaded daily weather data (wind speed, precipitation, and temperature) collected at Billings International Airport for the year 2021 from data stored on NOAA's National Centers for Environmental Information. I combined these data with patient records and PM 2.5 data to test for interactions between the linear regressions for PM 2.5 concentrations and weather variables against ED admissions.

Results:

The mean number of ED admissions averaged over three days after exposure to a PM 2.5 concentration differed significantly when daily PM 2.5 values were categorized as either greater than or equal to (risk) or less than (safe) the WHO guideline for 24-hour exposure $t(78.94) = 6.36$, $p < 0.001$ (Figure 4). The mean number of ED admissions for WHO risk days ($M = 105.64$)

was significantly higher than the encounters for WHO safe days (M = 93.75). The 95% confidence interval of the difference is 8.17 to 15.61 encounters.

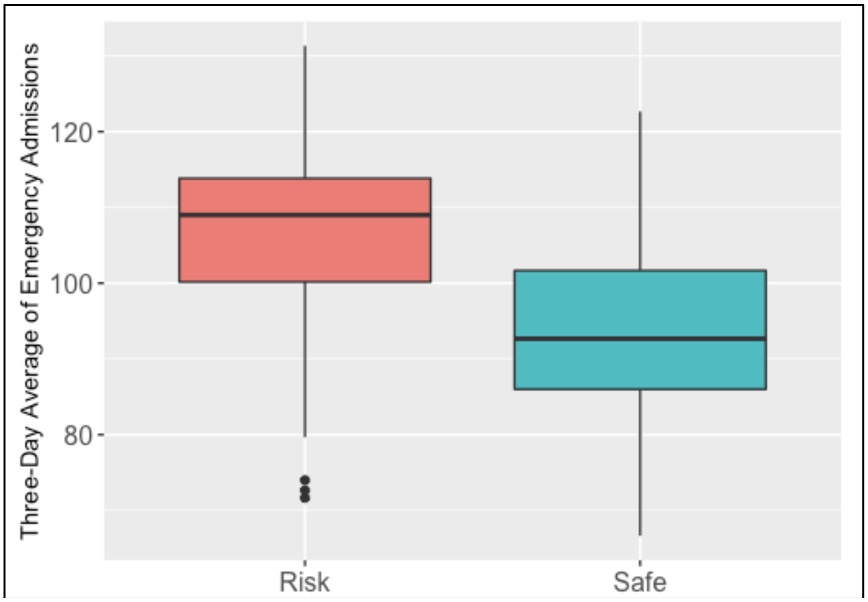

Figure 4: Boxplot Showing Differences in the Three-Day Average of Emergency Admissions Grouped by PM 2.5 Less Than 15 $\mu g/m^3$ ("Safe") and PM 2.5 Greater Than or Equal to 15 $\mu g/m^3$ ("Risk")

The mean number of ED admissions averaged over three days after exposure to a PM 2.5 concentration also differed significantly when daily PM 2.5 values were categorized as either greater than or equal to (risk) or less than (safe) the EPA guideline for 24-hour exposure $t(10.09) = 6.65$, $p < .001$. The mean number of encounters for EPA risk days (M = 113.77) was significantly higher than the encounters for EPA safe days (M = 95.39). The 95% confidence interval of the difference is 12.23 to 24.52 encounters.

There was a positive linear relationship between the concentration of PM 2.5 and ED admissions over a three-day period after exposure. The linear model predicts that every 10 $\mu g/m^3$ increase of daily PM 2.5 exposure would result in an average increase of: 15 (+/-1.5) all-cause ED admissions over a three day period (($p<0.001$) (Figure 6); 0.5(+/-0.02) respiratory ED admissions over a two-day period (p=0.02); and 0.5 (+/-0.02) cardiovascular ED admissions over a four-day period (p=0.002) (Appendix, Table C). Emergency admissions displayed an interaction between PM 2.5 concentration and wind speed (p<0.001) (Appendix C), but no interactions were found between PM 2.5 concentration and daily average temperature or precipitation on hospital admissions.

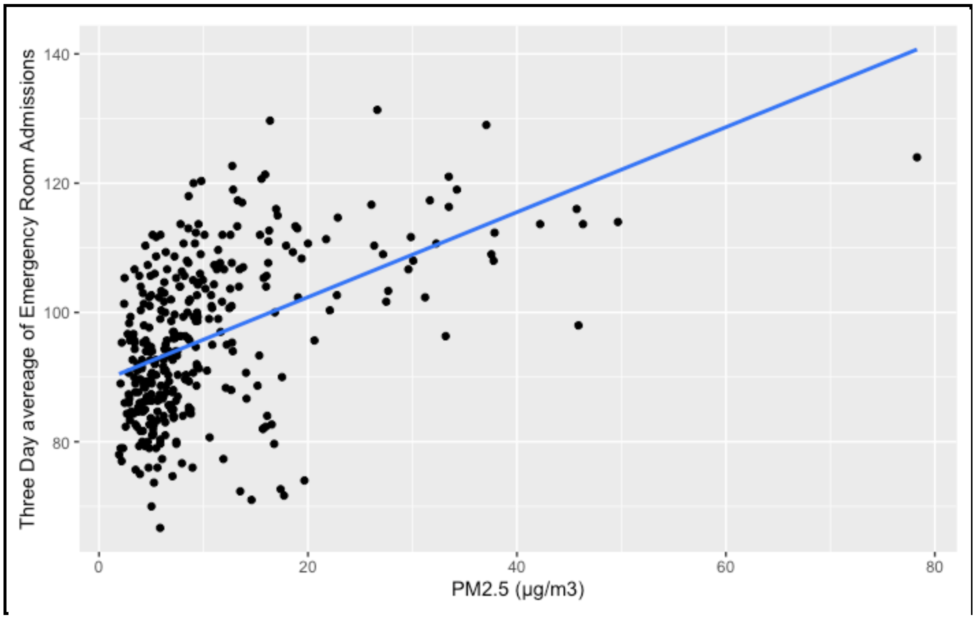

Figure 5: Linear Regression of PM 2.5 Concentrations and the Three-Day Average of Emergency Admissions Following Exposure at a Yellowstone County Hospital.

<u>Discussion</u>:

With climate change, wildfires are predicted to increase in their severity (Adams et al., 2021). As discussed in chapter 1, this will result in an increase of the 98th percentile PM 2.5 concentration, and the number of days the PM 2.5 concentration is above the WHO and EPA acute risk thresholds. In 2021, the year of this analysis, PM 2.5 concentrations for Yellowstone County ranged from 1.92-78.29 µg/m^3, with an average daily concentration of 10.18+/-9.06µg/m^3. This shows that the average daily PM 2.5 concentration is below both the EPA and

WHO acute thresholds for risk and that daily fluctuations on the order of 10 μg/m^3 are possible. An increase of 10 μg/m^3 would not only result in surpassing the WHO acute threshold for risk but would result in an increase of hospital admissions over a three-day period.

By applying percent increases from other linear regression models to the average encounters from the hospital in Yellowstone County, comparisons could be made to other studies. The prediction that all-cause emergency admissions would increase by ~15 additional encounters with each additional 10 μg/m^3 increase of PM 2.5 is much larger than Ye et al.'s prediction of a 1.65% increase informed by PM 2.5 exposure from wildfire smoke in Brazil. Applying their percentage to the 95.73 average emergency admissions would yield only 1.58 additional ED admissions at the Yellowstone County Hospital. The prediction of a 0.5 increase in respiratory ED admissions is approximately the same value yielded from Ye et. al's model of a 5.09% increase (applied to 10.3 avg. respiratory admissions), while the cardiovascular admissions are slightly lower than that predicted by Ye et al. of 1.1% (applied to 15.27 avg. daily admissions) resulting in an increase of 0.1 admissions. The predictions from Ye et al. were based on nationwide data that could be attributed to wildfire smoke, while this study is only based on one hospital in a geographically diverse state that experiences a high level of wildfire exposure. Furthermore, their data were based on a two-day average, while this study chose the time frame that showed the largest impact, which differed for all-cause (three-day average), respiratory (two-day average) and cardiovascular (four-day average).

Data from this study were limited to one hospital network within Yellowstone County, while there are at least four separate networks that serve this county with an emergency room. As a result, the true impact of PM 2.5 on health within Yellowstone County is incomplete. Accessing healthcare records is subject to lengthy reviews and is generally expensive, creating burdens for additional data in cases of low budget/ time restraints. While the year 2021 represents a period of exposure to wildfire smoke in Yellowstone County, not all increases in PM 2.5 concentrations (especially at lower concentrations) can be traced to wildfire exposure. If the particle components within PM 2.5 differ during different periods of elevated exposure, the impacts on health and hospital admissions may also differ throughout these time periods. Other pollutants with known health effects that increase during wildfires are ozone and VOCs, which were not accounted for in this analysis. Furthermore, the specific components of PM 2.5 (EC, metals, etc.) could vary depending on the burn location and those components could result in a greater or lesser severity of health impacts. In this study, all cardiovascular and respiratory diagnoses were grouped together for analysis, but to better understand health impacts and trends, diagnostic codes should be broken down by specific codes for diseases such as asthma or pulmonary embolisms, and data can be further analyzed by age group.

The original goal of this chapter was to make comparisons between two geographically distinct counties, Yellowstone, and Missoula; however, data from the Missoula hospital system were incomplete and unable to be used. These data would have been meaningful as they could help reveal trends for time periods where the AQI was deemed very unhealthy and ultimately hazardous. The conclusions from the Yellowstone County hospital study are limited in that PM 2.5 concentrations rarely reach classification as “unhealthy” as defined by the EPA; although this does occur once in the year 2021. In addition, Yellowstone County represents a geographical area where atmospheric pollutants are unlikely to pool, and thus elevated daily PM 2.5 is rarely prolonged. Being able to access hospital records in a geographical region where pollutants are more easily trapped can allow for a better understanding of the impact of consecutive days with an elevated AQI.

CHAPTER 3: AN ASSESSMENT OF RISK COMMUNICATION IN MONTANA

The goal of this exploration was to characterize risk communication of PM 2.5 exposure through reported daily AQI values by assessing the number of sensors in the state and analyzing those values within the context of national statistics for the number of sensors by population and land area, and Montana county population statistics. Furthermore, I completed an analysis to determine how the distances between three sensors in the same county and their vicinity to a wildfire impacts the accuracy of risk communication.

Comparison of PM 2.5 Sensors in Top-Ranked Wildfire States

Methodology:

I obtained statistics for the number of wildfires and acres burned for the 2021 year for each state from the National Interagency Fire Center (NIFC). I filtered data to include only the top 10 ranking states for acres burned. I obtained the total resident population for each state in 2021 from Statista, based on data from the U.S. Census Bureau (2021), and the total land area of each state from the U.S. World Review (n.d.). I downloaded PM 2.5 data for 2021 from the EPA for each of the 10 states, and the number of unique sensor site names were tabulated using R. I chose to include sensors, even if they only included a partial year of data, as any time monitoring occurs, it can provide a more accurate estimate of PM 2.5 concentration and communicate risk. Additionally, temporary sensors may monitor during times/ seasons of historical risk, such as the summer and wildfires. I calculated the number of sensors per: 100,000 miles squared of land area, million residents, and 100,000 acres burned, and ranked each state based off of the ratios of sensors by land area, resident population, or acres burned.

Results:

In 2021, Montana had the 3rd highest number of acres burned amongst all U.S. states. Compared with the top 10 U.S. states for acres burned in 2021, Montana ranked 10th in the number of sensors per 100,000 acres burned estimated at 3.9 sensors/100,000 acres; it ranked first in the number of sensors per resident estimated at 26.4 sensors per million residents; and ranked 7th in the number of sensors per land area estimated at 19.9 sensors per 100,000 miles squared (Table 8).

Table 8: Sensor Statistics from 2021 for the Top 10 States Ranked by Acres Burned.

State	Rank by Acres Burned in 2021	Sensors/ 100,000 Acres Burned in 2021	Sensors/ Million Residents	Sensors / 100,000 mi^2 of Land Area
California	1	7.7	4.4	110.4
Oregon	2	6.2	12.0	53.1
Montana	3	3.9	26.4	19.9
Washington	4	9.9	8.7	100.8
Arizona	5	6.7	4.8	30.8
Idaho	6	5.2	12.1	27.8
Alaska	7	4.3	14.3	1.9
Texas	8	32.1	1.8	20.7
Kansas	9	4.9	2.7	9.8
New Mexico	10	15.3	9.0	15.7

Assessment of Montana Sensors by County:

Methodology:

I obtained population data by Montana county from the 2019: Annual Estimate of Resident Population from the U.S. Census Bureau; this allowed each Montana county to be ranked by its population size, including counties with a sensor. I used the population estimates for each county to determine the approximate percentage of Montanan residents that have an official sensor in their county. I used the PM 2.5 data from 2021 to obtain the latitudes and longitudes of each sensor and input this location information into Google Earth Pro to spatially visualize the sensors throughout Montana. The two largest wildfires of the 2017 season were the Lodgepole Complex Fire and Rice Ridge Fire. I included Jordan, MT in Garfield County, the most populated area near the Lodgepole Complex Fire of 2017, and Seeley Lake, MT of Missoula County, the most populated area near the Rice Ridge Fire of 2017 on this map as wildfire reference points.

Results:

Taking the sum of the populations for each county with a sensor and dividing that by the total state population, 79% of state residents have an AQI sensor in their county. The top 10 populated counties in Montana are served by at least one air quality sensor, although the Lake County sensor monitors for less than 50% of the calendar year (Table 9).

The top 10 most populated counties make up 73% of the 79% of residents with a sensor in their county, and apart from Yellowstone and Cascade Counties, eight of these counties are in

Table 9: Montana Counties with an AQI Sensor Ranked by Population *Gray rows indicate counties in eastern Montana. *When Number of sensors provides a fraction, this indicates a sensor that records data for less than 50% of the year.*

County	Population	Population Rank	Number of sensors
Yellowstone	161,300	1	1
Missoula	119,600	2	3
Gallatin	114,434	3	2
Flathead	103,806	4	1.5
Cascade	81,366	5	1
Lewis and Clark	69,432	6	2.5
Ravalli	43,806	7	1
Silver Bow	34,915	8	1
Lake	30,458	9	0.5
Lincoln	19,980	10	1
Sanders	12,113	16	1.5
Fergus	11,050	18	1.5
Roosevelt	11,004	19	0.5
Richland	10,803	20	1.5
Rosebud	8,937	25	1.5
Powell	6,890	29	0.5
Phillips	3,954	38	1
Sheridan	3,309	41	0.5
Powder River	1,682	48	1

western Montana. There are still several sensors in the less densely populated eastern counties, some located in counties with less than 10,000 residents; this indicates that the MTDEQ has tried to not only serve the most populated counties, but also provide sensors and communicate risk to the eastern section of the state. Figure 6 shows that there is a greater concentration of sensors in western Montana within the mountain/ valley topography than the eastern region of the state where there are large areas without sensors. This map also shows the relative distance of sensors near 2017's two largest fires. Seeley Lake, the closest town near the Rice Ridge Fire, has a PM 2.5 sensor and there are two others within the same county. Jordan, MT, the closest town near the Lodgepole Complex Fire, has no sensors in a close vicinity. Using the line measurement tool in Google Earth Pro, it was determined that the closest year-round sensor was ~80 miles northwest in Phillips County.

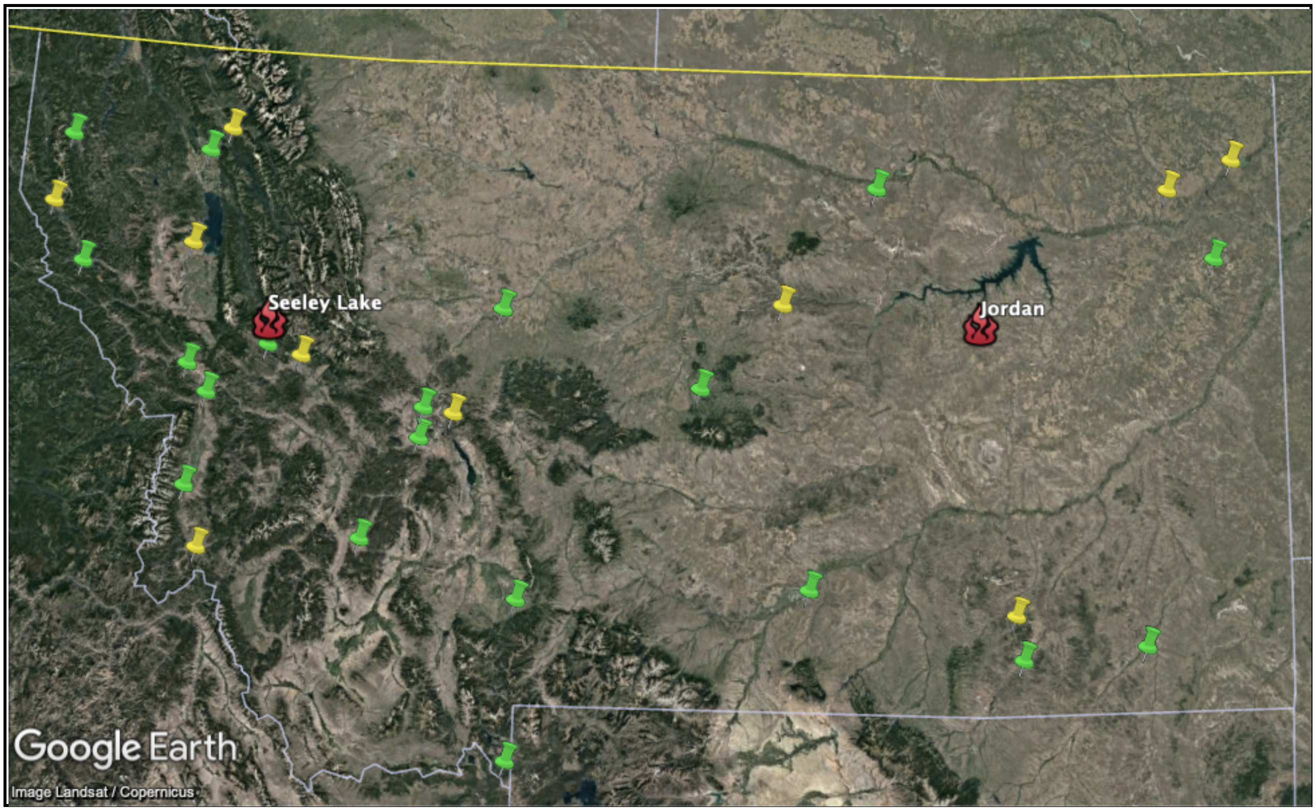

Figure 6: Location of PM 2.5 Sensors in Montana in 2021 (Author's image created in Google Earth Pro). *Yellow pins represent sensors recording less than 50% of data for the year, while green pins represent sensors that recorded more than 50% of data for the year. Jordan and Seeley Lake are also included with a fire symbol as a reference point to the two largest fires of the 2017 wildfire season.*

Discussion:

Given Montana's large size and low population, it is not surprising to find that it ranked first in its ratio of sensors to people and ranked seventh in its ratio of sensors per land area. Even though Montana has the greatest density of sensors per person when compared to other states threatened by wildfires, given its large land area and acreage burned, there still may not be enough sensors to adequately assess and communicate risk, especially to residents living in remote areas, far from a sensor at the time of a wildfire. While there is a relatively high density of sensors in Western Montana, there is more land overall in the eastern part of the state and large stretches of land where there are no sensors. The Lodgepole Complex Fire burned over 270,000 acres (the worst on record of 2017), mostly within Garfield County and along the border of Petroleum County (DES Lodgepole Fire Archive (n.d.)) and this just happened to be in an area with no air quality sensor nearby. Although the Rice Ridge Fire occurred in the direct vicinity of a sensor, wildfires by nature are random and the greater the density of monitoring locations, the more likely that the PM 2.5 concentration emitted from that fire can be accurately recorded and reported to the public.

Analysis of Multiple Sensors within one county during a Wildfire

Methodology:

I plotted the latitudes and longitudes of the three permanent sensors for Missoula County in google earth and estimated the geographical vector distances between each sensor in kilometers (km). I downloaded both PM 2.5 and Daily AQI values from the EPA for the year 2017 for Missoula County sensors. Since daily AQI is what's reported to the public, I chose to analyze AQI values for this analysis. Using excel, I calculated the absolute difference in Daily AQI values for each day of 2017 (where data was collected) between each site. I categorized AQI data for the 2017 year into two groups: the duration of (and slightly after) the Rice Ridge Fire (July 24th- September 13th) and all other dates of 2017 excluding the fire. I calculated the average absolute difference between each site for these two groups of data. Using excel, I plotted the average absolute difference in AQI values versus the average distance between sensors and fit this with a linear trendline to examine how distance from a sensor during a wildfire impacts the difference in daily AQI values.

Results:

Figure 7 shows daily AQI values for the three sensors in Missoula County throughout 2017. The Rice Ridge Fire began July 24th and ended September 4th. According to a report from Wildfire Today from August 29th, 2017, that utilized fire maps from inciweb, the fire came within 1.5 miles of Seeley Lake, and evacuations were ordered for the community (Gabbert 2017). While an exact distance of the fire to the sensor at Seeley Lake Elementary School is unknown, it is clear this is the closest sensor to the fire.

The average absolute difference of AQI values between the three Missoula sensors during the fire and before/after the fire were calculated and show that for most of the year, the sensors

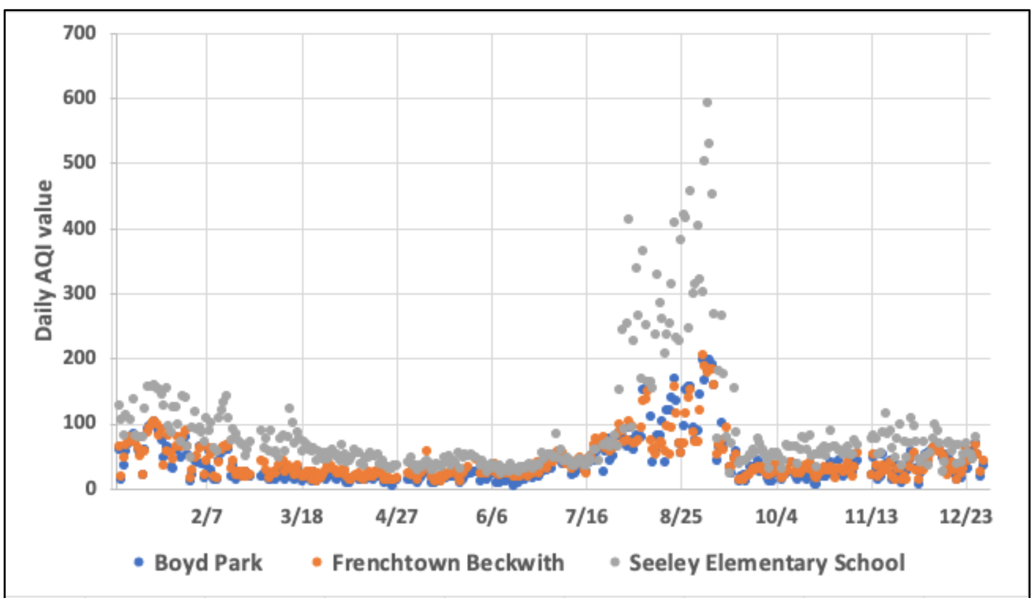

Figure 7: Display of Daily AQI Values Between Three Sensors in Missoula County During 2017.

have an absolute difference in AQI values below 30. The Boyd Park and Frenchtown-Beckwith sensors are approximately 25 km apart, and their average AQI difference is 7.2±5.2; the difference increased during the time of the Rice Ridge Fire to 15.1±13.6. The Boyd Park and Frenchtown-Beckwith sensors are approximately 25 km apart, while the sensor at Seeley Lake Elementary School is approximately 55 km away from the Boyd Park sensor and 60 km away from the Frenchtown-Beckwith sensor. As a result, the typical (non-fire) average difference between AQI values for Seeley Lake when compared to Frenchtown-Beckwith (29.0±20.9) and Boyd Park (33.5±20.5) are much greater than the average difference between Boyd Park and

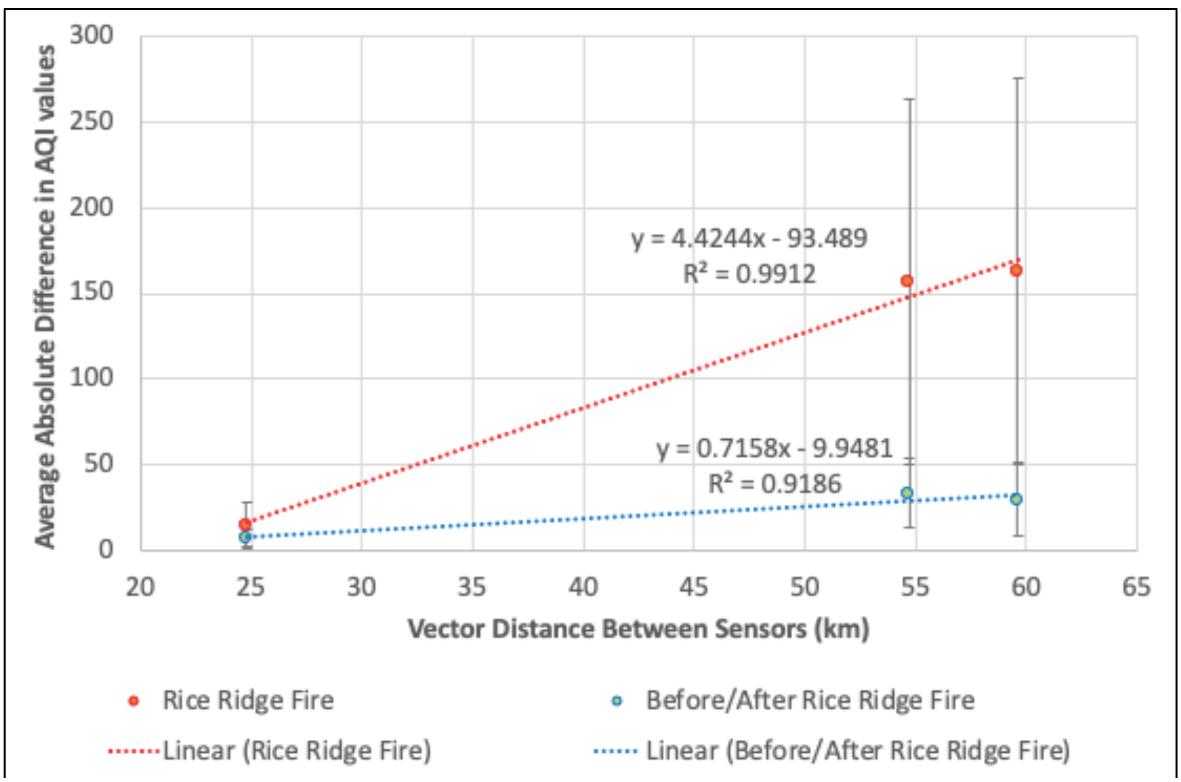

Figure 8: Relationship Between the Distance Between Sensors (km) and the Average Absolute Difference in AQI Values Between the Three Sensors of Missoula County During and Before/After the Rice Ridge Fire of 2017 PM 2.5. *Error bars represent standard deviation.*

Frenchtown-Beckwith sensors (7.2±5.2). The difference in AQI values is exacerbated during and slightly after the time of the Rice Ridge fire (July 24th- September 13th) (Figure 7). The average AQI difference between the Frenchtown-Beckwith and Boyd Park sensors roughly doubled (15.1± 13.6) during the time of the Rice Ridge Fire, but the difference between the Seeley Lake sensor and Frenchtown-Beckwith (112.0±29.0) and Boyd Park (106.6±33.5) sensors more than tripled.

The average absolute differences between each sensor were plotted during the time of the fire and before/after the fire and fitted with a linear trend line (Figure 8). While based on limited data, both trend lines show that greater distances between sensors result in greater differences in AQI values, but that during a wildfire, the average differences increase, especially when comparing the Seeley Lake sensor (closer to the fire) with sensors further away.

Discussion:

Missoula County is unique in that it has three sensors, and the analysis shows that readings for each sensor differ throughout the year, providing unique insight to risk for individuals who live in proximity to a given sensor. This observation was especially true for the wildfire that was near Seeley Lake in 2017. If Missoula County did not have the sensor at Seeley Lake elementary school, residents in this area would be relying on data from one of the other two sensors and the AQI readings on average would have been over 100 points lower than their true values; however, this statistic does not capture the extremes as the maximum absolute difference was 415. For example, on September 6th, the AQI reading for Seeley Lake was 593 ("Hazardous”), while the readings for the other two sensors ranged from 178-181

(“Unhealthy”). While the residents of Seeley Lake would have likely been aware of risks on account of proximity to the fire, the sensor provides additional data that is useful both during and after the fire. First off, this data allows for the MTDEQ’s to record the most accurate PM 2.5 values and translate this to AQI values and warnings that ranged from “Very Unhealthy” and “Hazardous” on most occasions during the fire. This information would be provided on MTDEQ’s Today’s Air website, which also includes links for activity recommendations with increasing AQI, guidance for schools, and information about health impacts from wildfire smoke. The information recorded from the MTDEQ is also incorporated in the EPA’s Airnow.gov website that provides up to date AQI values on a national scale. In addition, having monitors near wildfires will allow for health impacts from PM 2.5 wildfire smoke to be studied retrospectively, which can result in a better understanding of its impacts on human health, which can improve guidelines and breakpoints for NAAQS, and possibly result in regulations to further reduce emissions where possible.

While more sensors will result in more accuracy, there are no recommendations for a specific distance that results in a loss of accuracy. Many environmental factors have been reported to impact PM 2.5 concentrations, including temperature, precipitation, pressure, relative humidity, wind speed and wind direction (Li et al. 2017). Therefore, as distance between sensors increases so does the likelihood that environmental variables will differ and as a result so will PM 2.5 concentrations. While this study was able to conclude differences in PM 2.5 values between sensors, it did not deduce environmental factors that would contribute to these differences.

CONCLUSION:

The two worst years for wildfires as measured by acreage burned (2017 and 2021) in the past five years showed the most risk for acute PM 2.5 exposure for Montanans as all counties exceeded the WHO acute threshold within those years and more than half of the counties exceeded the much higher threshold from the EPA standards. PM 2.5 concentrations (98th percentile and annual means), along with the percentage of days in a year that acute thresholds were exceeded were always higher in western counties, but eastern counties are not without risk as the five-year average 98th percentile PM 2.5 concentration exceeded the WHO threshold and in 2021 the EPA threshold was exceeded. Furthermore, the dates when the PM 2.5 concentration exceeded the WHO or EPA thresholds in eastern counties almost exclusively occur within fire season. As acreage burned increased, so did the percentage of days above the acute thresholds, and 2017 and 2021 showed the highest average frequency of days exceeding these thresholds statewide. A relationship was established that as the percentage of days above acute thresholds increases, so does the annual mean, and thus with increasing acute exposure, the risks from chronic exposure may also increase. These initial findings suggest that wildfires lead to an increased risk of acute PM 2.5 exposure statewide, and that repeated acute exposure may lead to chronic risk.

By analyzing records from one hospital system in eastern Montana for the 2021 year, it was established that emergency admissions were significantly higher (over a three-day period following exposure) when the PM 2.5 concentrations were above both the WHO and EPA thresholds. Linear regressions also showed positive relationships between all-cause, cardiovascular, and respiratory emergency admissions with increasing PM 2.5 concentrations;

however, these predictions are highly limited as they were based on one hospital, in one county of Montana.

Montana is a large, relatively rural state, and its ten most populated counties have at least one sensor monitoring for a portion of the calendar year, and 79% of the population have a sensor within their county of residence. There is a greater density of sensors in western Montana than eastern Montana which is much larger in overall area and lower in population, with large areas without any sensors. This study showed that as distance from a wildfire increases, the difference in AQI (based on PM 2.5) values increased. Therefore, the further away a location is from a PM 2.5 sensor, the less accurate the PM 2.5 value for estimating risk. Sensor deserts (common in eastern Montana) not only reduce the accuracy of AQI values during periods of wildfires, but also prevent or reduce the accuracy of follow up studies for PM 2.5 exposure and human health for these populations. Since Montana is one of the top five U.S. states for wildfires, increasing the number of PM 2.5 sensors throughout the state would be prudent.

Wildfires are a common part of life in Montana and climate change models predict an increase in wildfire frequency and severity in the future. The Climate Change and Human Health Report in Montana (2021) states a lack of data connecting wildfire smoke and human health for the state (Adams et al. 2021). While research has established health impacts from PM 2.5 exposure, the chemical composition of PM 2.5 varies by source and (burn) location and as a result, health impacts and predictions can vary (Jaffe et al. 2020). Therefore, it is essential that environmental agencies (MTDEQ and the EPA), health networks, and academic researchers work in unison to prepare for the future. Efforts should be made by these organizations to protect human health and properly communicate wildfire related risk, particularly when risks cannot be mitigated, which is often the case with wildfires. To build the most accurate predictions of risk for Montanans, hospital records should be analyzed from a statewide level, and historical records and maps of wildfire smoke exposure can be used to determine if increased PM 2.5 from wildfire smoke has a different impact on human health as similar increases of PM 2.5 concentrations from other sources (possibly winter temperature inversions). Having retrospective studies specific for a rural, wildfire affected state and its different geographical regions will help provide the most accurate information about the health impacts from PM 2.5 exposure to Montanans, enabling healthcare providers and the MTDEQ to better understand and communicate these risks to the public.

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APPENDICES

APPENDIX A

WILDFIRE STATISTICS FOR THE STATE OF MONTANA (2017-2021)

Year	**Number of Wildfires**	**20-year rank of number of wildfires**	**Acres Burned**	**20-year rank of acres burned**
2017	2,422	4	1,366,498	1
2018	1,342	17	97,814	15
2019	1,474	13	64,835	16
2020	2,433	2	369,633	7
2021	2,573	1	747,678	5

*Ranks are based on data from 2002-2021.

**Data obtained from the National Interagency Fire Center

APPENDIX B

PERCENTAGE OF DAILY PM 2.5 VALUES EXCEEDING 24-HOUR EXPOSURE THRESHOLDS FOR THE EPA OR WHO FOR EACH COUNTY (2017-2021)

Geography	County	Percentage of daily PM2.5 values exceeding 24-hour exposure guidelines for:									
		EPA					WHO				
		2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
Western Mountain	Flathead	3.40	4.38	0.28	3.03	3.02	17.56	15.89	7.80	7.48	12.67
	Gallatin	0.43	0.85	0.00	2.47	1.73	11.32	5.52	1.28	5.63	14.10
	Lewis and Clark	5.51	1.99	0.33	3.75	3.75	19.41	7.81	7.62	4.32	11.96
	Lincoln	3.86	6.08	0.28	4.68	4.68	30.30	32.87	30.03	29.75	37.74
	Missoula	10.92	0.77	0.37	5.69	5.21	34.36	18.38	14.60	16.36	21.74
	Ravalli	11.48	0.00	0.00	2.23	6.50	26.05	10.50	5.23	7.80	13.84
	Sanders	7.07	3.94	0.00	2.19	5.97	28.26	14.08	3.90	6.28	15.06
	Silver Bow	7.49	0.24	0.00	2.15	5.49	27.91	8.94	7.97	9.07	15.51
Eastern Plains	Cascade	0.58	1.67	0.28	0.84	3.01	8.99	6.11	1.38	3.90	9.86
	Fergus	1.92	1.65	0.00	0.82	3.01	6.85	5.22	0.56	4.10	9.04
	Phillips	1.12	1.12	0.00	0.30	0.91	5.04	4.47	0.55	11.14	10.64
	Powder River	2.58	0.56	0.00	1.22	3.49	17.48	9.75	1.97	12.50	17.73
	Richland	0.82	0.60	0.00	0.00	1.18	6.53	3.87	0.84	0.55	9.76
	Rosebud	2.49	0.58	0.00	1.67	4.61	10.53	6.12	1.44	7.36	19.15
	Yellowstone	1.40	1.16	0.34	0.82	2.94	10.67	8.43	1.03	6.59	18.53

APPENDIX C

STATISTICAL RESULTS FROM LINEAR REGRESSIONS PERFORMED ON ACRES BURNED OR ANNUAL MEAN PM 2.5 FOR VARIOUS RESPONSE VARIABLES

Explanatory Variable	Response Variable	Fitted Regression Model	R^2	F stats	p-value
Acres Burned	98th Percentile PM 2.5	$y=21.3+3*10^{-5}x$	0.20	F(1,73)=19.27	<0.001
Acres Burned	Percentage of Days Above Acute EPA Risk	$y=0.96+ 2.6*10^{-5} x$	0.25	F(1,73)=26.2	<0.001
Acres Burned	Percentage of Days Above Acute WHO Risk	$y=7.44+8*10^{-6}x$	0.18	F(1,73)=17.6	<0.001
Acres Burned	Annual Mean PM 2.5	$y=6.2 + 3.5*10^{-6}x$	0.21	F(1,73)=21.14	<0.001
Annual Mean PM 2.5	Percentage of Days Above Acute EPA Risk	$y=5.3 + 1.2x$	0.81	F(1,73)=324.7	<0.001
Annual Mean PM 2.5	Percentage of Days Above Acute WHO Risk	$y=3.73+0.37x$	0.66	F(1,73)=145.3	<0.001

APPENDIX D

STATISTICAL RESULTS FROM LINEAR REGRESSIONS PERFORMED ON DAILY PM 2.5 CONCENTRATIONS AGAINST A GIVEN RESPONSE VARIABLE FOR HOSPITAL ADMISSIONS (YELLOWSTONE COUNTY, 2021).

Response Variable	Fitted Regression Model	R^2	F stats	p-value
Emergency encounters, lag 0-2	y=209+ 1.49x	0.21	F(1,343)=94.27	<0.001
All respiratory emergency encounters, lag 0-1	y=12.26+ 0.05x	0.01	F(1, 344)= 5.26	0.022
All cardiovascular emergency encounters, lag 0-3	y=13.56+ 0.05x	0.02	F(1, 342)=9.71	0.002
Emergency encounters, lag 0-2 * Daily Average Wind Speed	y=93.48 + 0.10x	0.19	F(3,343)= 28.91	0.002