Where There’s Fire, There’s Smoke: Examining Population Exposure to $PM_{2.5}$ from Prescribed Burning in Northeastern Washington

Alexandra Dolk

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington
2021

Reading Committee:
Ernesto Alvarado, Chair
Alison Cullen

Programs Authorized to Offer Degrees:
School of Environmental and Forest Sciences

University of Washington

Abstract

Where There’s Fire, There’s Smoke: Examining Population Exposure to $PM_{2.5}$ from Prescribed Burning in Northeastern Washington

Alexandra Dolk

Chair of the Supervisory Committee:
Ernesto Alvarado
School of Environmental and Forest Sciences

Prescribed burning is receiving wider scientific and political recognition as a tool for reducing wildfire risk and mitigating the impacts of future wildfires. Indeed, Washington DNR's 2017 Forest Health Strategic Plan set a goal of conducting mechanical treatments and prescribed burning on 1.25 million acres of Washington's forests over the next 20 years. However, the risk of smoke from prescribed burning impacting local communities is not well understood. Therefore, prescribed burning is highly regulated, limiting the achievement of this goal. This thesis examines the impacts to air quality as a result of smoke from a set of broadcast burns in North-central and Northeastern Washington in 2019. We compare spatial and temporal data from prescribed burning permits with 24-hour average $PM_{2.5}$ concentrations recorded by a network of permanent air quality monitors and low-cost sensors. Our analysis found the network of air quality monitors and sensors is inadequately distributed in relation to prescribed burning activity to fully measure population exposure to $PM_{2.5}$ using sensors and monitors alone. However, where prescribed burns did occur near air quality monitors and sensors, three out of 22 prescribed burns had nearby monitors or sensors register $PM_{2.5}$ concentrations above 35.5 $\mu g/m^3$, the maximum set by the National Ambient Air Quality Standards. 1,411 people were within 16 kilometers of all three burns.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to thank my committee members, Dr. Ernesto Alvarado and Dr. Alison Cullen for providing their support and expertise on a wide variety of wildfire and prescribed fire science and policy topics throughout this research.

I am grateful for the National Science Foundation funding that allowed me to be hired as a research assistant on the project, “Managing Future Risk of Increasing Simultaneous Megafires” (Award #2019762). The award supported me through two quarters of schooling, allowed me to meet and work with some very brilliant researchers in the fire world, and provided a valuable introduction to prescribed fire policy and management. Thank you to Dr. Alison Cullen and Dr. Susan Prichard for their support and leadership as part of that project.

Thanks to my lab mates Colton and Harry for regularly sharing their knowledge on prescribed fire, and for their feedback on this research. Thank you also to Harry for making the database of historical prescribed burn permits available.

Many thanks to the USFS Pacific Wildland Fire Sciences Lab Airfire team for developing the PWFSLSmoke R package and making it available for researchers.

Thank you to my good friend Eva, whose expertise in R made compiling and sorting hundreds of thousands of rows in Excel spreadsheets significantly less arduous. Despite working on her PhD research a whole continent away, she still found time to help me whenever I asked.

And finally, to thank you Kyle for moral support along the way, for reading and editing my thesis paper, and for cooking dinner almost every night for the past three months.

1. EXECUTIVE SUMMARY

We ask the question: In 2019, did prescribed burning in this region have an impact on the air quality of nearby populations? In this case, “impact” is defined as 24-hour average $PM_{2.5}$ concentrations above 35.5 $\mu g/m^3$, the maximum concentration set by the National Ambient Air Quality Standards. Prescribed burning is the intentional use of fire to achieve ecological, economic, or cultural objectives. This research uses Washington Department of Natural Resources (“DNR”) records of prescribed burn activity, data from permanent government air quality monitors and low-cost air quality sensors, and fine-scale population data to examine prescribed burning impacts to air quality in a region of central and eastern Washington State. In the first stage of answering this question, we explored the spatial distribution of permanent regulatory monitors and low-cost PurpleAir sensors in the region. While there are pockets of population centers well-covered by sensors and monitors, such as the Methow Valley, many areas, including some that may be exposed to wildfire or prescribed burning smoke, lack adequate monitor and sensor coverage. The coverage and gaps of the monitoring network is therefore analyzed in this thesis.

In the next stage, we studied the potential air quality impacts of a set of 60 broadcast burns in 2019. Where monitors and sensors existed within 16 kilometers of one of these burns, we collected 24-hour average $PM_{2.5}$ observations from those monitors and sensors. We then examined how many sensors or monitors registered 24-hour average air quality, on the day of a nearby prescribed burn, above the NAAQS maximum (and the degree to which the air quality exceeded that maximum). Finally, we estimate the total population within 16 kilometers of those burns that had monitors and sensors within 16 kilometers register NAAQS exceedances, as this population may have been exposed to unhealthy air quality.

Our study found three out of 22 prescribed burns had nearby air quality monitors and sensors that registered 24-hour average $PM_{2.5}$ above the NAAQS maximum on the day of the burn. In those three burns, an estimated 2,270 people may have been exposed to 1 day of 24-hour average $PM_{2.5}$ concentrations above the NAAQS maximum. An estimated 244 people may have been exposed to at least two days of 24-hour average $PM_{2.5}$ concentrations above the NAAQS maximum. Further, an estimated 1,411 people may have been exposed to three days of 24-hour average $PM_{2.5}$ concentrations above the NAAQS maximum.

In sum, this thesis reaches two conclusions. First, that the air quality monitor and sensor network is inadequate for understanding the full impact of prescribed burning on air quality. Second, that the majority of burns we studied did not result in air quality impacts in populated areas, though this conclusion is significantly limited by uncertainty regarding the direction the smoke travelled on the day of the burn and other factors.

2. INTRODUCTION

2.1 Past and current fire regimes in Washington & the Western U.S.

Fire has had a regular presence in many North American forests for millennia. Prior to European settlement, seasonally dry forests, such as the Ponderosa pine and mixed conifer forests of eastern Washington, regularly experienced frequent low-, moderate-, and mixed-severity fires (Agee, 1993). Fires were ignited by lightning. They were also ignited by Native American tribes, who intentionally modified the environment around them for a variety of purposes, including the cultivation of culturally-useful plants for food, medicine, and basketry, improving ease of travel, and managing and promoting hunting grounds (Pyne, 1982; Stewart et al, 2002; Vale, 2002; Trauernicht et al, 2015; Long et al, 2021). These fires molded the environment, encouraging fire tolerant species — such as Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) — and keeping forest stands open with few shrubs or small trees (Agee, 1993). Surface fuels were minimal and spaced intermittently (Agee, 1993).

The arrival of Euro-American settlers in North America dramatically altered existing fire regimes. Deadly Eurasian diseases introduced to the continent significantly reduced indigenous populations and by extension led to an initial reduction of fire on the landscape (Ryan et al, 2013). In the 1700s, Euro-American settlers spread across the continent, clearing forest land for agriculture and livestock grazing, generating exceptional quantities of fine woody debris and logging residue along the way (Ryan et al, 2013). A focus on timber resources and the expansion of settlers into fire-prone areas shaped a Euro-American view of fire on the land as something to be prevented and suppressed wherever possible. Active fire suppression efforts, led by the federal government, began in the late 19th century and persisted for most of the 20th century.

The combination of reduced burning by tribes and fire exclusion and suppression policies was reflected in a significant decline of total area burned in the Western United States between the 1920s and 1970s (Littell et al, 2009).

Without low- and moderate-severity fires regulating vegetation growth, stand densities increased and tree species susceptible to fire crowded into formerly open forests (Agee, 1993). Hazardous accumulations of surface fuels began to accumulate (Agee, 1993). At the same time, forest management practices driven by timber production promoted higher stand densities and favored fire-intolerant tree species (Taylor, 2004; Nowacki & Abrams, 2008).

This confluence of landscape changes, combined with variations in climate, created conditions prone to very large, high-severity fires (Parks & Abatzoglou, 2017). At the same time, accidental human-caused ignition of fire dramatically increased (Balch et al, 2017; Cattau et al, 2020). Thus, after decades of declining, total area burned in the Western U.S. eventually began to increase in the 1970s (Littell et al, 2009). Though it's debated whether the overall rate of high-severity fires in Western U.S. dry forests from 1984 on is within historical ranges (Baker, 2015), in Washington State the trend is clear: the proportion of high-severity fires in dry forests that would have historically experienced low- and mixed-severity fires has increased for the past four decades (Hessburg et al, 2000; Podschwit et al, 2019; Haugo et al, 2019).

Wildfires have a range of significant direct and indirect impacts on the ecology of a landscape. High-severity wildfires that reach tree crowns and kill a significant portion of the trees in a stand are known as stand-replacing fires. Forests that fail to recover after such fires may convert to a different forest type, or be replaced by non-forest vegetation altogether (Stevens‑Rumann et al, 2018; Coop et al, 2020). Such changes in vegetation can disrupt hydrological systems, leading to flooding, debris flows; erosion, and sediment build-up in streams and rivers (Parise, 2011; Thompson et al, 2013; Wine et al, 2018). Fires that burn at high-severities can directly kill wildlife species at the time of the burn, or indirectly impact their populations through post-fire changes in habitat and ecological functions. For example, one study found spotted owl populations reduced after medium- and high-severity burns (Rockweit et al, 2017).

Increases in the size and severity of wildfires in recent decades has also had severe social consequences. Wildfire events along the wildland urban interface (WUI) can prompt mass evacuations, destroy homes, result in injuries and loss of life to people, and lead to cascading impacts on communities (Radeloff et al, 2005; Stein, 2013; Bracmort, 2018; Spearing & Faust, 2020; Dye, et al 2021). Moreover, wildfire smoke contains pollutants that are associated with negative health impacts, including increased risk of respiratory disease and cardiovascular disease (Liu et al, 2015, Aguilera et al, 2021). One study estimated 92.2 deaths in Washington State in 2020 could be attributed to exposure to wildfire smoke from the California and Oregon wildfires that summer (Liu et al, 2021). At the federal level, rising fire suppression costs eat into Forest Service budgets and draw resources away from other forest management activities — a situation known as “fire borrowing” (Hoover, 2020; NIFC, 2020).

Heading into the mid-21st century, the combination of climatic changes and increasing anthropogenic ignitions are projected to lead to more severe wildfire seasons (Cattau et al, 2020; Halofsky et al, 2020). Models predict an increase total area burned by “uncharacteristic” fire (fire of a severity, size, or duration not historically seen in a particular landscape), as well as lengthened fire seasons (Littell et al, 2010; Stavros et al, 2014; Barbero et al, 2015; Washington

DNR, 2020). The likely future wildfire regime will further stress our already taxed ecological and social systems.

2.2 History & current use of prescribed burning in the Pacific Northwest

Prescribed burning is the intentional use of fire to achieve a specific ecological, economic, or cultural objective. Though a long-standing tool used by several Pacific Northwest tribes for millennia, prescribed burning saw a significant reduction in use after Euro-American settlement in the region, as a direct result of fire suppression policies and federal actions that confined native peoples to specific areas and assigned control of most of their ancestral lands to federal and state governments (Boyd, 1999; Long & Lake, 2018; Long et al, 2021). Prescribed burning did not entirely disappear from the landscape. Harold Weaver, a forester for the BIA stationed in the Pacific Northwest, studied, documented, and advocated for the extensive and effective use of prescribed burning to reduce logging slash and mitigate fire risk on the Colville National Forest and the Confederated Tribes of the Colville Reservation (Weaver, 1943; Weaver, 1947). Nor did the memory of traditional burning practices disappear from reservoirs of traditional ecological knowledge passed down by generations of tribal members (Boyd, 1999; Long et al, 2021). Some of the loudest calls for returning fire to the land have come from tribes and groups keen on restoring landscapes and cultures that depend on traditional burning (Lake et al, 2017; Flesher, 2021; Long, et al, 2021; Marks-Block et al, 2021). However, Washington, like the rest of the country, has seen a significant decline in the use of prescribed burning.

Returning low- and mixed-severity fire regimes to landscapes through increased use of prescribed burning has potential to restore landscapes and mitigate future wildfire impacts

(Kolden, 2019). For this reason, in the past two decades prescribed burning has received wider scientific and political recognition as a tool for reducing wildfire risk and mitigating the impacts of high-severity fires (Mitchell et al, 2009; Prichard et al, 2021; Cochrane et al, 2012; Stevens et al, 2012; Calkin et al, 2014). The 2000-2001 National Fire Plan — the first of its kind — included investments in thinning and prescribed burning as one of its key recommendations (Glickman et al, 2000). Subsequent federal fire management strategies and plans all prioritized prescribed burning as a tool for mitigating severe wildfire impacts and restoring ecosystem health (Healthy Forests Restoration Act of 2003, 2003; FLAME Act, 2009; Wildland Fire Leadership Council, 2014).

Despite the increased attention, across the Northwest, use of prescribed burning has continued to decline since 1998 (Kolden, 2019) Eastern Washington specifically has seen the annual area burned by prescribed fire and yearly total number of days on which prescribed burning happens decline since 2004 (Podschwit et al, 2021). But in 2017, Washington DNRs' 20-Year Forest Health Strategic Plan set a goal of conducting mechanical treatments and prescribed burning on 1.25 million acres of eastern Washington forests over the next 20 years (Washington Department of Natural Resources, 2017). Thus, amidst declining use of prescribed burning, there is a recognition that it is a beneficial and necessary tool for land managers to use in restoring landscapes and reducing the risk of catastrophic wildfire.

2.3 Air quality impacts of prescribed burning

Despite its numerous beneficial ecological effects, prescribed burning is not entirely without risks. Smoke from prescribed burns, like that from wildfire, contains particulates, nitrous oxides, and volatile organic compounds that can adversely affect human health. Fine particulate matter smaller than 2.5 microns in diameter, known as $PM_{2.5}$, travels deeply into human respiratory tracts and can have a range of serious impacts to human physiology, including damage to respiratory and cardiovascular functions (Williamson et al, 2016). The impacts of $PM_{2.5}$ inhalation for an individual typically depend on length of exposure and the unique physiological conditions of that individual. People with existing respiratory conditions such as asthma or COPD, young children, and older adults are often particularly sensitive to fine particulate matter, (Fan et al, 2015; Chi et al, 2019). For this reason, $PM_{2.5}$ is one of the pollutants regulated by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act. $PM_{2.5}$ emissions are commonly the focus of studies that examine prescribed burning and wildfire impacts to air quality and human health.

Regulatory requirements around prescribed burning in most states require prescribed burning to be conducted in a way that does not lead to air quality impacts to nearby populated areas (Washington State DNR, 1998). The method with which a burn is ignited and managed, the vegetation that is burned, meteorological conditions, topography, and a variety of other factors influence how much smoke a prescribed burn produces, and where the smoke travels (Miller et al, 2019). However, air quality in urban areas can be degraded when smoke from prescribed burning travels into the area, an event called a smoke intrusion or smoke incursion (Miller et al, 2019).

In a review of the processes that influence wildland fires and prescribed fires, Jaffe et. al. noted that the body of science on the health impacts of wildfire is rapidly growing, but “substantially less research has been done on the health impacts arising from prescribed burning." (Jaffe et al, 2020). Much of the literature on prescribed burning smoke impacts to air quality and human health is focused on the Southeastern U.S., where prescribed burning is a prominent source of $PM_{2.5}$ (Johnson et al, 2019; Huang et al, 2019; Afrin, et al, 2021). Studies of prescribed burning in Georgia have estimated that prescribed burning in 2016 led to an average increase in annual $PM_{2.5}$ concentration of 0.9 $\mu g/m^3$ across the state (Afrin et al, 2021).

In Washington, prescribed burning is the source of a relatively small percentage of total emissions of $PM_{2.5}$. Washington State's 2017 Emissions Inventory reported that prescribed burning accounted for less than 2% of $PM_{2.5}$ emissions (Washington Department of Ecology, 2020). In comparison, wildfires are the source of nearly 62% (Washington Department of Ecology, 2020). The difference in contributions is a result of both the greater amount of area burned by wildfire compared to prescribed fire (Podschwit et al, 2021) and the fact that prescribed burning tends to emit less $PM_{2.5}$ per area burned than wildfire (Hyde & Strand, 2019). Still, relatively little research has been done on the impacts of prescribed burning on air quality in the Pacific Northwest. Ravi et al (2018) used a smoke modeling framework in combination with a health impact assessment tool to estimate the air quality and health impacts of prescribed burn activities in the Pacific Northwest. They estimated health impacts from prescribed burning in 2011 led to "280–700 additional deaths, 4400 lower respiratory symptom cases, 7300 upper respiratory symptom cases, around 400 acute bronchitis cases, and several thousand workday losses." (Ravi et al, 2018). However, the authors noted that the brunt of prescribed burning impacts in their study were seen in western Oregon, northern Idaho, and western Montana.

2.4 Barriers to prescribed burning

A variety of social, regulatory, environmental, and economic factors hinder the use of more prescribed burning on landscapes. The barriers to conducting more prescribed burning are extensive and systemic, and may not be surmountable with a single ‘silver bullet’ solution (Schultz et al, 2019). One factor is budgetary. In recent years, rising fire suppression costs have consumed federal land management budgets and left little financial room for fuel treatments and other forest health activities (States News Service, 2014). Land managers at the BLM and the forest service most often cite lack of adequate funding and personnel as a barrier to doing more prescribed burning (Quinn-Davidson & Varner, 2012; Schultz et al, 2019). Though not as commonly cited as a barrier, public perception of prescribed burning and public tolerance of smoke can also play a role in hindering prescribed fire use. The 2018 National Prescribed Fire Use Survey Report indicated that public perception was a larger barrier to prescribed burning in the West than in any other U.S. Region (Melvin, 2018). However, in Washington, relatively strict air quality regulation has been touted as one of the major barriers to prescribed burning (Schultz et al, 2019). Another barrier is the complex regulatory environment in which prescribed burning is permitted, which is discussed in detail below.

2.5 Federal regulations concerning air quality

Prescribed burning operates under an intricate framework of local, state, and federal regulations. At the federal level, the Clean Air Act is the primary law that regulates air quality and air pollution in the United States, including that from prescribed burning (U.S. EPA, 2021b). The U.S. Environmental Protection Agency (EPA) administers the Clean Air Act in cooperation with states, an arrangement known as cooperative federalism (Williams, 2021). The EPA has set standards for six pollutants, including $PM_{2.5}$, known as the National Ambient Air Quality Standards (NAAQS), that identify a maximum concentration of each pollutant over a certain period of time. These maximum concentrations are ceilings above which human health, visibility, and the integrity of buildings, animals, and vegetation may be compromised or harmed (U.S. EPA, 2021b). The EPA delegates certain responsibilities of implementing the Clean Air Act, and maintaining the NAAQS, to states.

While the Clean Air Act requires states to regulate pollution such that air quality meets the NAAQS, emissions from wildfire smoke are exempted from the EPA's assessment of a state’s adherence to the standards. This is called the exceptional events rule. Some have argued this setup creates a perverse incentive against prescribed burning, as the activity that has enormous potential to improve air quality in the long term is heavily regulated while wildfires receive no such scrutiny (Williams, 2021).

2.6 Washington’s Smoke Management Plan

Every state that has been delegated the authority (by the EPA) to implement the Clean Air Act also has a State Implementation Plan (SIP) that must be approved by the EPA. A state’s SIP is the suite of regulations, ordinances, statutes, and plans that set forth how the state will maintain the NAAQS. The EPA approves changes to the SIP and will sanction states that do not maintain compliance with the NAAQS.

Washington’s Smoke Management Plan (“The Plan”) is an element of Washington’s SIP. The Plan is written and updated by Washington’s DNR in consultation with the Department of

Ecology, and outlines the DNR's plan for managing and permitting prescribed burning. The Plan applies to "lands protected by the DNR and on unimproved, federally-managed forest lands and participating tribal lands" (Washington DNR, 1998). Non-participating tribal lands belong to those tribes that have been granted authority, by the EPA, to implement the Clean Air Act and oversee prescribed burning through their own agencies, such as the Confederated Tribes of the Colville Nation and the Spokane Nation, within the study area. In effect, the vast majority of prescribed burns that fall within Washington's borders are regulated by DNR's Plan. The Plan specifies the procedures for applying for and conducting prescribed burns. Land managers wishing to conduct a prescribed burn must apply for and receive a burn permit from Washington DNR.

To receive permit approval, a burn must meet certain criteria outlined in the Plan. A land manager can apply for and receive a burn permit long before a burn, but a final decision as to whether a burn will be allowed is made on the day of the burn by a DNR Region Manager (Washington DNR, 1998). The Region Manager considers factors such as current and forecasted air quality, current and forecasted weather conditions, fuel moisture, scenic impacts, and the availability of suppression forces before giving final approval (Washington DNR, 1998). This final decision happens on the morning of a burn, and is referred to in the Plan and colloquially as the "go - no go decision." The Plan stipulates that data describing how the prescribed burn was accomplished, including acres of land and tons of fuel actually burned, must be reported to DNR within five days of the burn.

The 1998 version of the Smoke Management Plan is still in use, but an update, a draft of which was released in 2019, is under development and DNR is preparing to seek EPA approval.

The 2019 update makes “modest changes to burn decision timing, allowable burning seasons, and denial thresholds” (Cooper, 2019). A few changes may aid in the permitting of more prescribed burns. For example, while the 1998 Plan prohibits burns over 100 tons (90 kilograms) on Fridays through Sundays, June 15th through October 1st, the 2019 update to the Plan would eliminate that restriction (Hankins & Zirkle, 2021). In addition, the 1998 Plan’s requires the “go - no go” decision for a burn to be made on the day of the burn, but the 2019 update would allow the decision to be made the day before the burn by 4:30pm. Importantly, with regard to air quality near populations, the 2019 update would allow prescribed burns under 100 tons (90 kilograms) in urban growth areas — in the 1998 Plan, no burning is allowed in urban growth areas (Washington DNR, 1998; Washington DNR, 2019b). Urban growth areas are defined by the Growth Management Act as areas where “urban growth shall be encouraged and outside of which growth can occur only if it is not urban in nature” (RCW 36.70A.110)[1]. Practically speaking, these are areas in and around towns and cities, also areas where wildfire threatens property and human safety.

The update to the Smoke Management Plan drafted in 2019 is still in development and has not yet been approved by the EPA.

2.7 Overview of research

Motivated by the proposed update to Washington’s Smoke Management Plan that would allow some prescribed burning in urban growth areas, this study uses historical data from prescribed burn permits in Washington State and air quality data to examine the potential impacts

---

[1] RCW 36.70A.110 is the portion of Washington’s state code that concerns the designation of Urban Growth Areas. Available at https://app.leg.wa.gov/RCW/default.aspx?cite=36.70A.110.

to air quality from certain prescribed burns near populations in a portion of northeastern Washington. Based on $PM_{2.5}$ concentrations recorded by permanent regulatory air quality monitors and low-cost sensors, we estimate potential days of exposure to air quality exceeding the NAAQS. NAAQs $PM_{2.5}$ exceedances are defined as periods when the 24-hour average concentration of $PM_{2.5}$ exceeds $35.5\mu g/m^3$, equivalent to 100 on the Air Quality Index (see Appendix I).

3. METHODS

3.1 Study location

This study focuses on prescribed burning in a 5,973,577 hectare region of northeastern Washington State (see Figure 1). The region is bounded to the north by the Canadian border, to the east by the Idaho border, to the south by Interstate-90, and to the west by the Northwest, South Puget Sound, and Pacific Cascade DNR regions, which follow the crest of the Cascade Mountains.

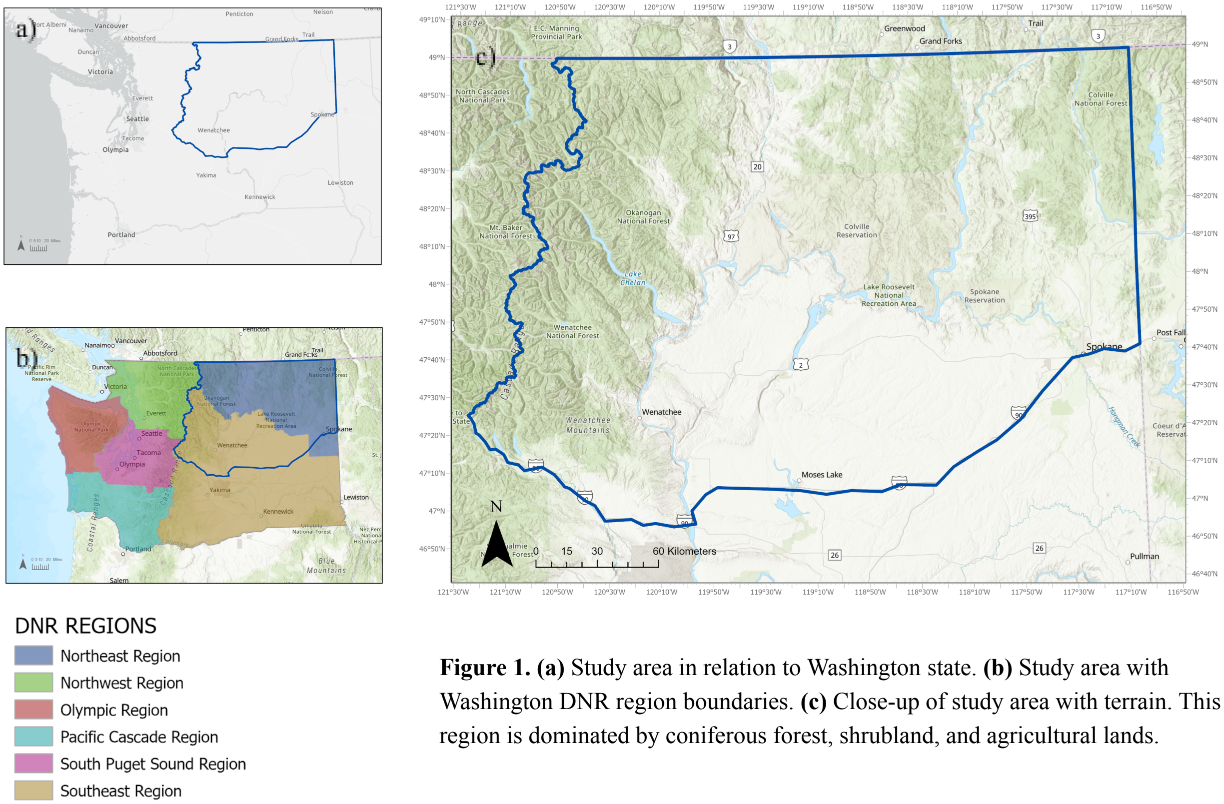


Figure 1. (a) Study area in relation to Washington state. **(b)** Study area with Washington DNR region boundaries. **(c)** Close-up of study area with terrain. This region is dominated by coniferous forest, shrubland, and agricultural lands.

We focus on the portion of DNR's Northeast Region and Southeast Region that is north of Interstate-90, to reduce the likelihood of air quality monitors recording emissions from prescribed burning of agricultural fields, a practice most common in Whitman and Walla Walla Counties in the southeastern corner of the state (Hansen et al, 2004). The study area was also selected because it has high concentrations of prescribed burn permit approvals. We also limited the study area to provide greater attention to specific fires and communities in Northeast Washington, with the hope that future studies will also evaluate prescribed burning impacts in Western and Southern Washington.

3.2 Data collection

3.2.1 Prescribed burn permits

This study uses Washington DNR prescribed burn permit request data from the years 2004-2019. The database of DNR burn permit requests was compiled by Podschwit et al (2021). In the data file, individual burn permit requests are organized by row; data pertaining to each request, such as burn date, requested burn acreage, and burn type, are recorded in columns. Prescribed burns are categorized as either pile or broadcast burns, per the 1998 Smoke Management Plan. Broadcast burns are burns of "debris on a designated unit of land, where the debris has not been piled or windrowed, by allowing fire to spread freely over the entire area." (Washington State DNR, 1998). Pile burns are burns of silvicultural waste that is piled into one location. Within our study area, 676 burn permit requests were made to Washington DNR in 2019.

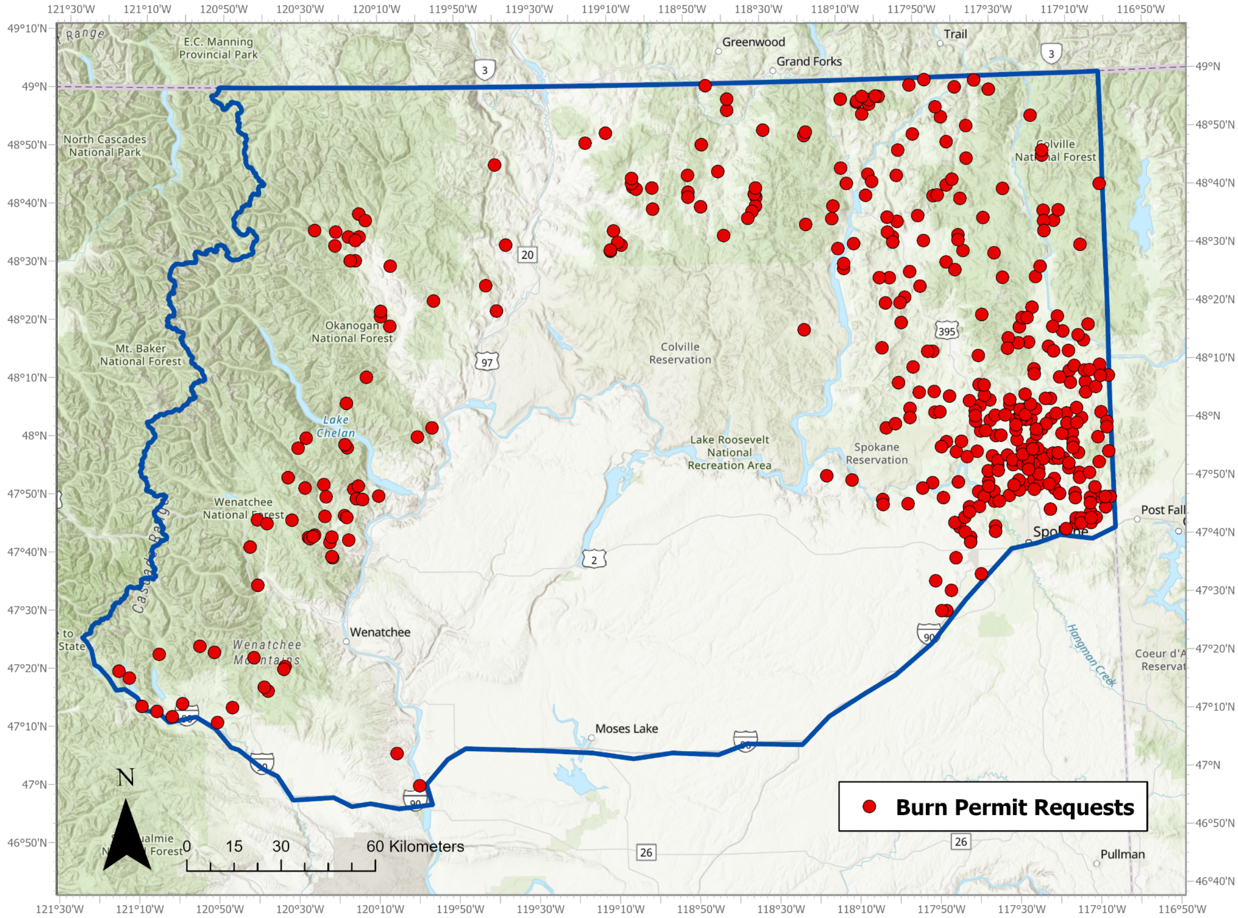


Figure 2. Map showing the locations of all prescribed burn permit requests submitted to Washington DNR 2019.

3.2.2 Air quality data

Air quality data from eastern Washington in 2019 was collected from two publicly available sources: AirNow and PurpleAir. AirNow is a partnership between the Forest Service, EPA, National Oceanic and Atmospheric Administration (NOAA), National Park Service, NASA, Centers for Disease Control, and air quality agencies at the tribal, state, and local levels. AirNow reports air quality readings from a network of permanent regulatory air quality monitors across the United States (henceforth referred to as 'permanent monitors'). These monitors are placed and maintained by regional EPA divisions, state air quality agencies and departments, and tribal air quality agencies. They remain in place permanently and provide continuous monitoring of air pollutants (AirNow, 2021; Washington State Department of Ecology, 2021). In Washington State, permanent monitors tend to be placed near population centers. There are 23 permanent monitors within the study area (see Figure 2).

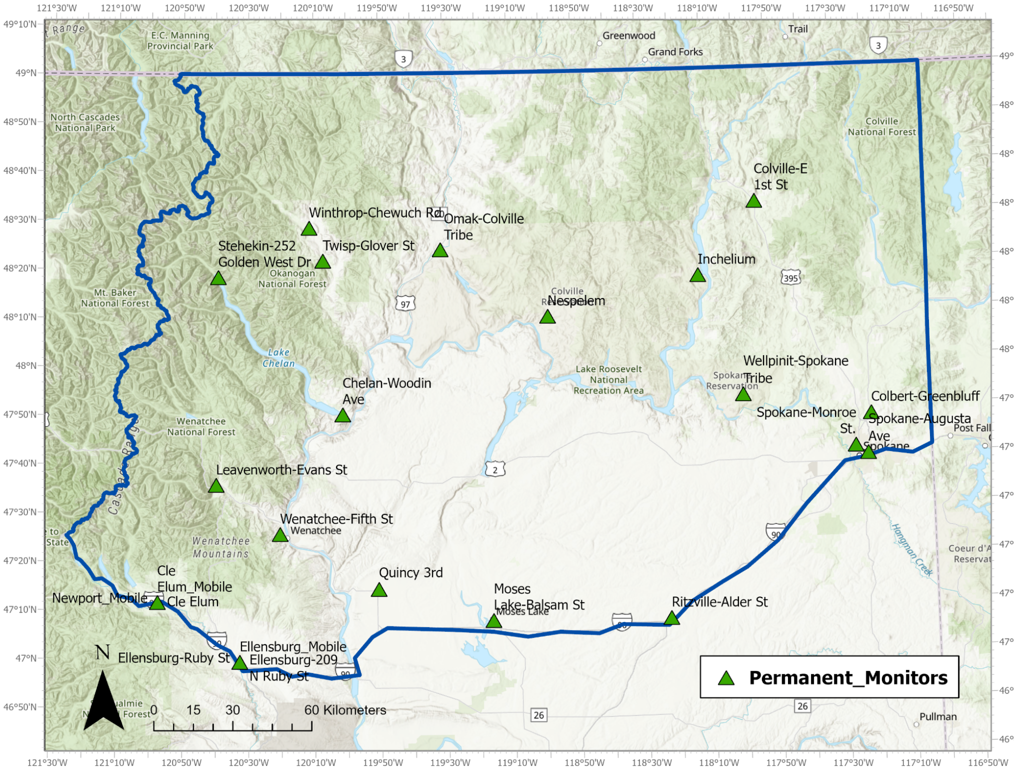


Figure 3. Map showing the locations and names of permanent regulatory air quality monitoring stations in the study area, adapted from Airnow.gov. Note that three monitoring stations in Cle Elum are represented by one green triangle on the map.

AirNow monitor data from the study area in 2019 was accessed via the PWFSLSmoke R package, developed by the USFS Pacific Wildland Fire Sciences Lab (Mazama Science, 2020). The PWFSLSmoke package was used to aggregate hourly $PM_{2.5}$ concentrations in $\mu g/m^3$ from every air quality monitor in Washington state, between midnight on December 31st, 2018 and midnight on December 31st, 2019.

Additional air quality data was available via PurpleAir.com. PurpleAir, Inc. produces low-cost air quality sensors, hereafter referred to as "sensors," which can be purchased by individuals, businesses, agencies, or community groups (etc.) and are used to monitor indoor or outdoor $PM_{2.5}$ levels. The sensors can be registered, which allows data collected by those sensors to be added to the PurpleAir map, which displays each sensor's readings of $PM_{2.5}$ concentration in $\mu g/m^3$ according to the EPA's Air Quality index scale, with the EPA's conversion factor for wildfire and woodsmoke conditions applied (PurpleAir Inc, 2021). The EPA conversion factor was developed to improve the accuracy of PurpleAir sensor observations of particulate matter concentrations during wildfire smoke episodes (Johnson et al, 2020; Barkjohn et al, 2021). PurpleAir sensors were first registered in the study area in 2018. By the end of 2019 there were 67 outdoor sensors in the study area (see Figure 3).[2]

---

[2] The Methow Valley area is particularly well-covered by these sensors due to a program launched in 2018 by Clean Air Methow: the Methow Valley Clean Air Ambassadors. This program created a network of businesses, schools, municipalities, and private citizens hosting PurpleAir sensors. In 2019, 20 of the PurpleAir sensors in the Methow Valley were part of this program. In addition, there were 11 other PurpleAir sensors outside of the Ambassadors program hosted by individuals, businesses, and municipalities in the Methow Valley. The cluster of sensors east of the Methow Valley is a network installed by the Okanogan River Airshed Partnership.

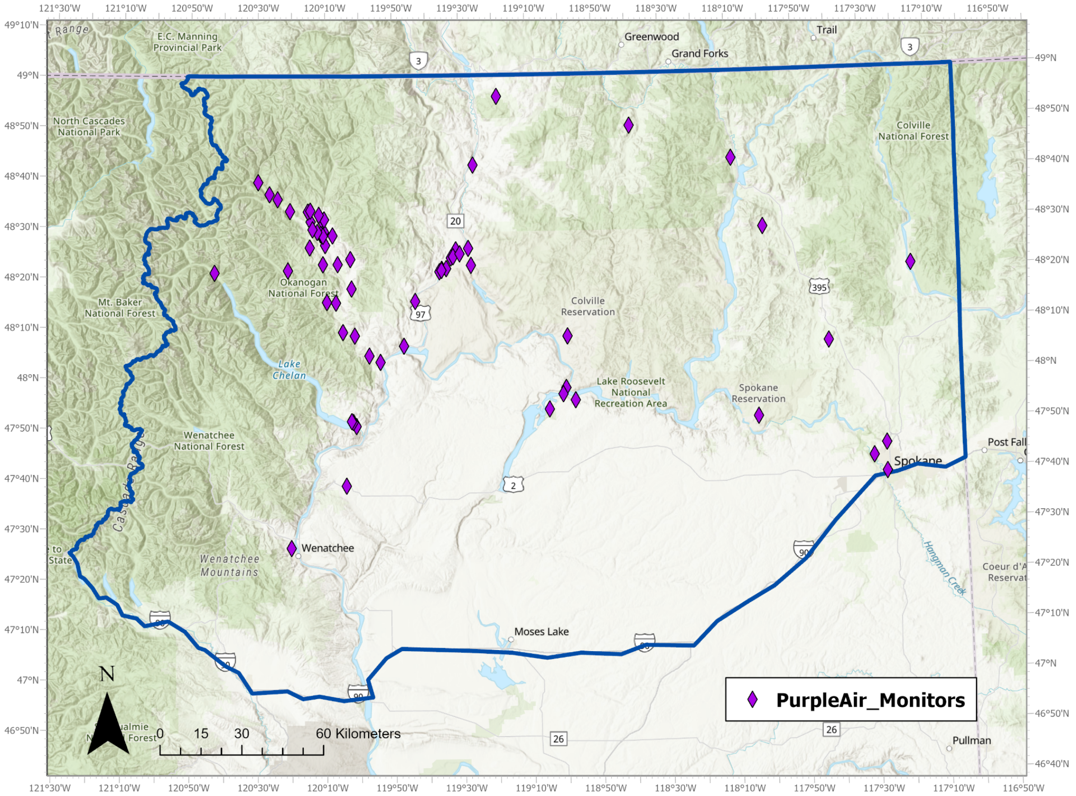


Figure 4. Map showing the locations of PurpleAir low-cost sensors in the study area, including the names of major cities. (PurpleAir Inc, 2021).

$PM_{2.5}$ observations from publicly registered sensors can be individually downloaded from PurpleAir's website (map.purpleair.com). We downloaded hourly average and 24-hour average $PM_{2.5}$ concentration data from these sensors for every day between midnight on December 31st, 2018 and midnight on December 31st, 2019.

3.2.3 Population data

We use fine-scale, publicly available 2019 population data from Oak Ridge National Laboratories' LandScan dataset (Oak Ridge National Laboratories, 2021).[3] The data is formatted as a count of population per one km^2. The LandScan data represents the ambient population in an

---

[3] More information about the Landscan dataset is available at https://landscan.ornl.gov/.

area — the population over an average of 24 hours. LandScan population data is developed "using best available demographic (Census) and geographic data, remote sensing, and imagery analysis techniques [...] to disaggregate census counts within an administrative boundary." (Oak Ridge National Laboratories, 2021).

The Landscan 2019 dataset came in raster form and was imported intoArcGIS Pro for geoprocessing. Each pixel represents a 1km^2 area, and the count value associated with the pixel is the estimated total ambient population in that area.

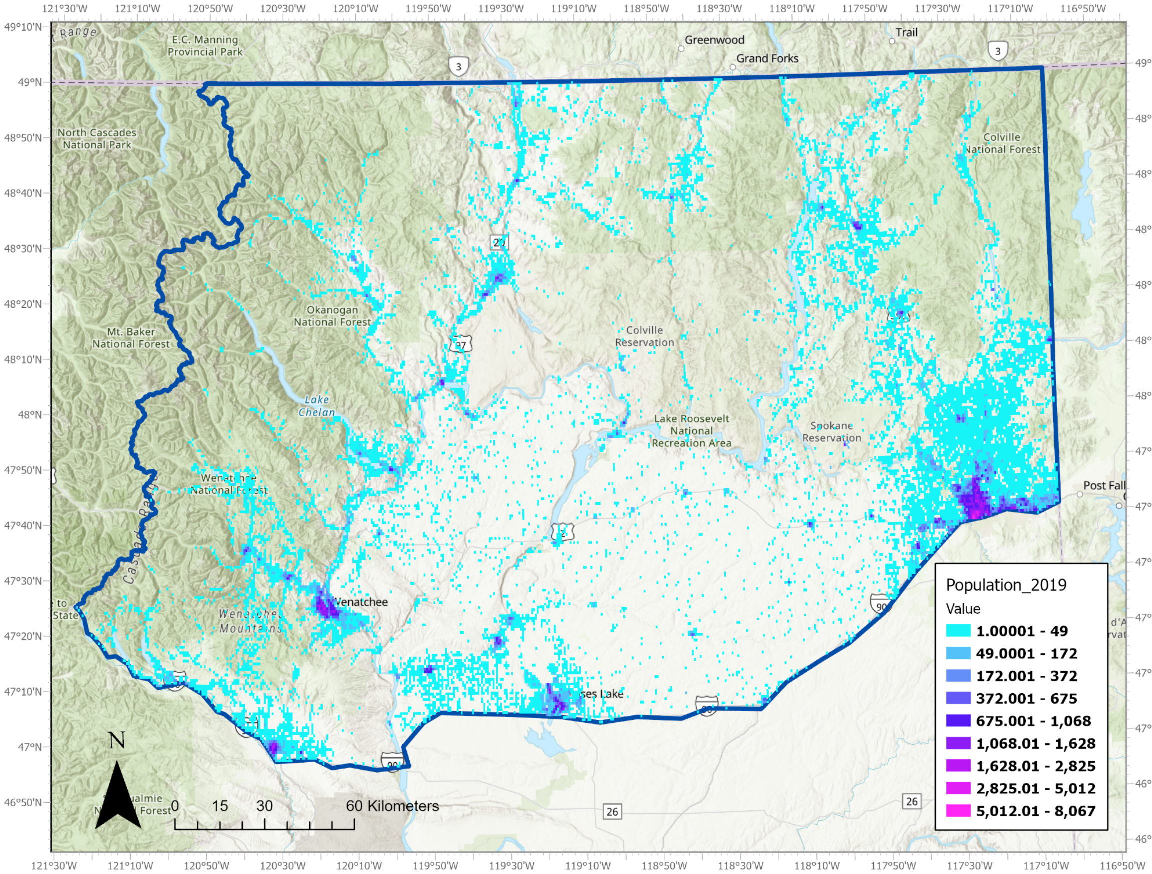


Figure 5. Map showing ambient population distribution in study area (modified from the Oak Ridge National Laboratories LandScan dataset).

3.3 Data preparation and analysis

3.3.1 Filtering the burn permit requests

A single datapoint in the burn permit dataset represents one request for a prescribed burn. However, not every burn permit request results in an approved burn. Additionally, in 2019, there were several permit requests for burns that happened in the same location, either over the course of multiple consecutive days or at different times throughout the year. We treat a single burn on a single day as the individual unit of analysis; thus, there are several burns in 2019 that overlap spatially (see Figure 7). Note that burns happening in the same location on multiple days may have been approved under the same permit if they are part of the same overall burn operation, but because the dataset treats these as individual burns, our analysis will as well.

Within our study area, there are 676 burn permit requests from the year 2019. Of these, the majority (80%) were for pile burns. The other 20% of these requests were for broadcast burns. For the purpose of this research we examine only broadcast burns (non-pile burns). There were 136 non-pile burns in 2019.

Burn permit requests for burns projected to burn over 100 tons (91 megagrams) of fuel must receive approval at the DNR Regional and the Division level; we therefore consider a burn permit request approved if it received a 'Yes' decision from both levels (Washington DNR, 1998). There were 104 approved non-pile burns in 2019.

The permit request data does not explicitly state whether a burn was conducted or not. It is possible for a burn request to have been approved, but the burn postponed to a different day or cancelled. However, post-burn information in the form of tons and acres accomplished (burned) was available for approximately half of the approved non-pile burns in 2019. For the purpose of this study, we identify a burn as having been completed if it has a value greater than zero for either tons or acres accomplished. Subsequent analysis focuses only on prescribed burns that have been completed. There were 60 completed and approved non-pile burns in 2019 (see Figure 8). While the burns without completion data may also have occurred, without subsequent reporting, we cannot know for sure and including them in the study area potentially risks skewing the results.

Figure 6 illustrates the filtering process by which we arrived at the final set of 60 prescribed burns used in our analysis. Figure 7 shows the spatial distribution of the 60 approved, non-pile completed burns in 2019. Figure 8 shows the numeric distribution of the same burns in terms of tons of fuel burned.

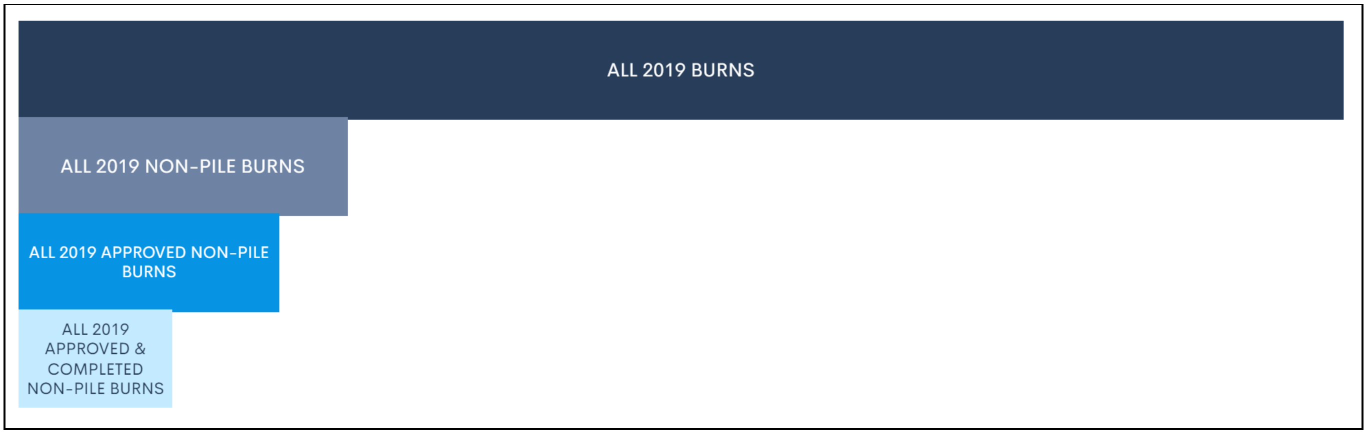


Figure 6. Visual illustration of how the initial set of 676 burn permit requests from the study area in 2019 were filtered to the final set of 60.

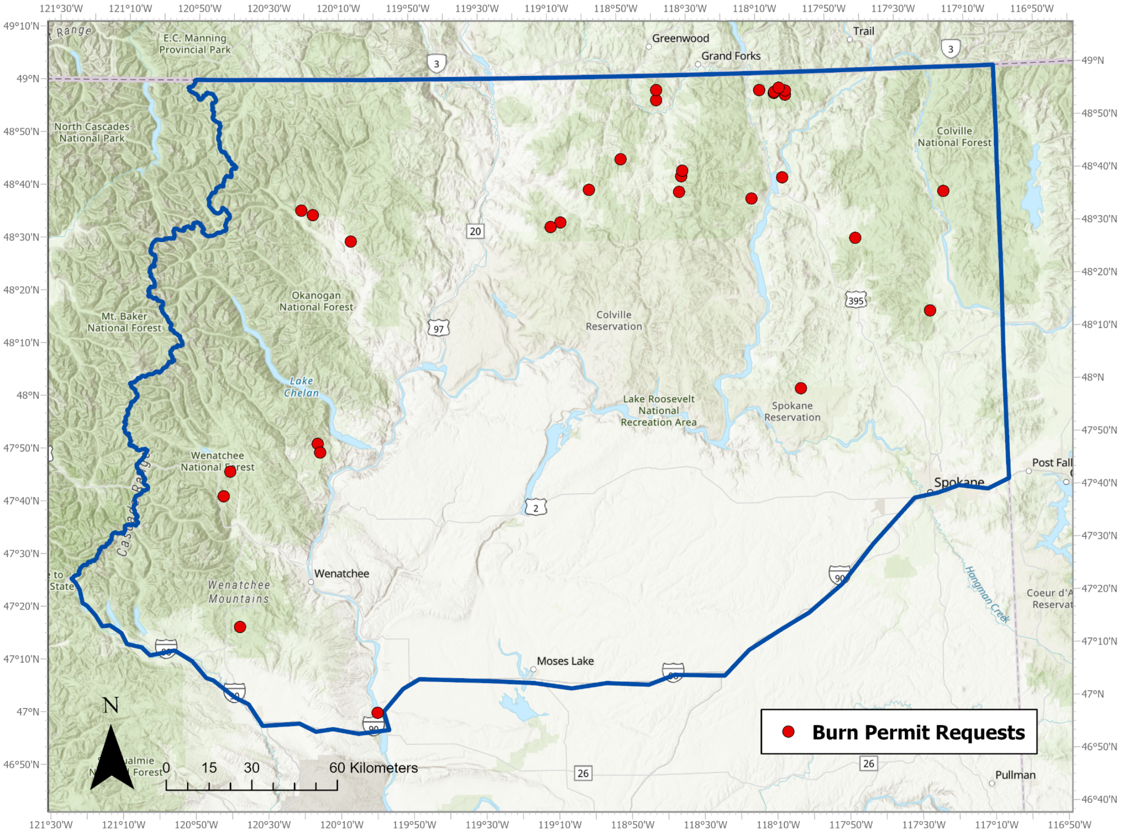


Figure 7. Map showing the final set of 60 prescribed burns in the study area in 2019.

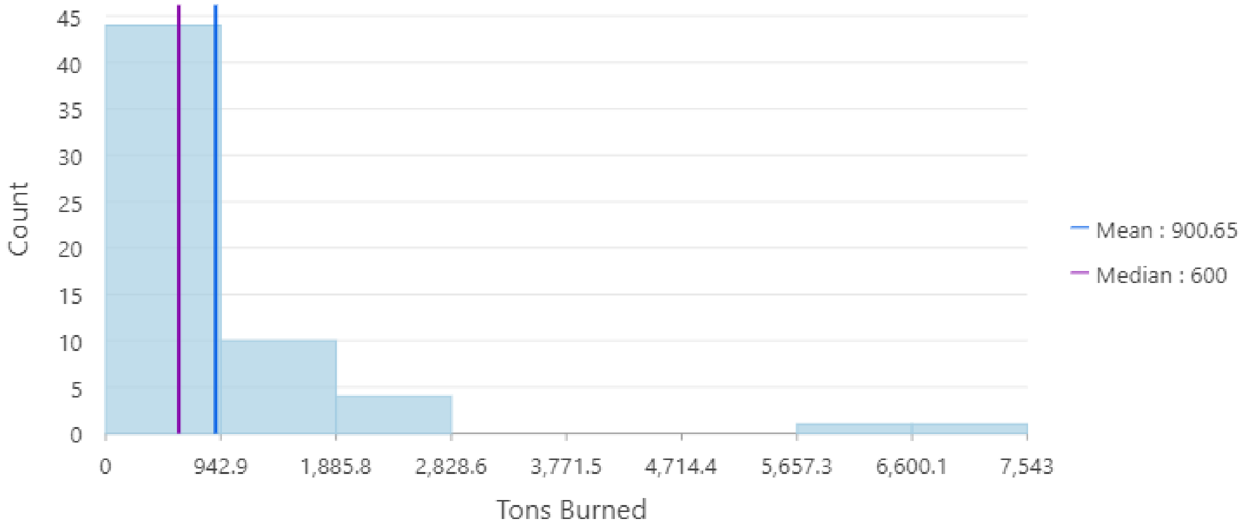


Figure 8. Histogram showing the distribution of the final set of 60 broadcast burns, by reported tons burned. The blue vertical line indicates the mean at 900 tons (816 megagrams). The purple vertical line indicates the median at 600 tons (544 megagrams).

3.3.2 Mapping air quality monitors and sensors

We began by mapping the locations of the permanent regulatory monitors and the PurpleAir low-cost sensors. An Excel spreadsheet containing coordinate locations for each regulatory monitor was produced via the PWFSLSmoke package in R. After loading the table into ArcGIS Pro, the monitor locations were displayed as a point feature class using the display X Y Data tool.

Low-cost sensor data required somewhat more manipulation before mapping. To our knowledge, a publicly available dataset containing the coordinates of all PurpleAir sensor locations does not exist, so we created one for all PurpleAir sensors within the study area PurpleAir's Sensor Data Download Tool, which allows downloads of air quality data from registered sensors in a particular region. One can use the PurpleAir Map (https://map.purpleair.com/) to specify the region of interest, then use the Download Tool to download air quality data for every sensor within that region. We downloaded a datafile for every PurpleAir Sensor in eastern Washington, then extracted the coordinates and sensor names from the datafile name using a program in R. We then created a feature point layer with those sensor locations in ArcGIS using the Display X Y Data tool. Finally, we merged the permanent monitors layer and the PurpleAir sensors layers into one, to display the spatial distribution of all sensors and monitors within our study area.

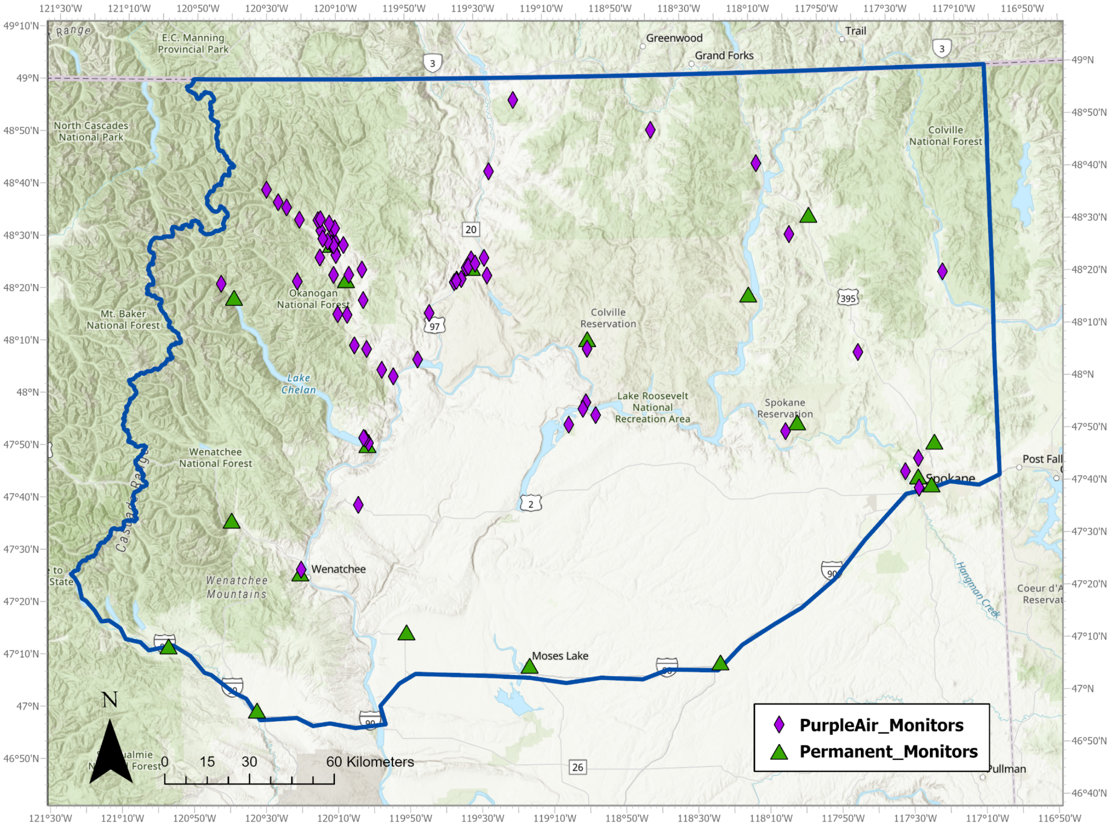


Figure 9. Map showing the locations of all permanent monitors and PurpleAir sensors that existed in 2019 in our study area.

We conducted a series of geospatial analyses to learn more about the distribution and coverage of permanent monitors and PupleAir sensors in relation to where people were in 2019 and where the 2019 prescribed burns were located.

First, we used the Raster to Point tool to turn the population raster into a point layer, wherein each point is located at the center of each 1km^2 raster cell (see Figure 10).

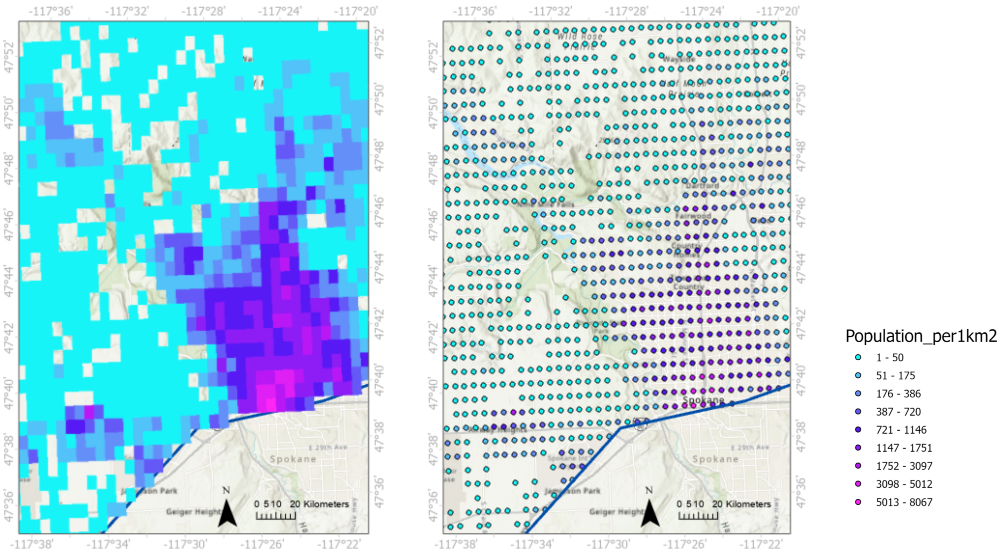


Figure 10. A comparison of the population layer, as a raster (left) and the population layer as points, wherein each point is at the center of a 1km^2 area, and is colored according to population count within that 1km^2 area.

We then used the Generate Near Table tool to create a table that listed the distance to the nearest monitor or sensor from each point in the population layer. Finally, we joined the table associated with the population point layer to the distance-to-monitors table. This added the count of population within each 1km^2 cell back into the dataset. As a result, we had a set of data in which each point, which represented the center of a 1km^2 area where people live, had an associated distance to the nearest monitor or sensor and the count of people within that area. Finally, to understand which areas were densely populated but lacked air quality monitoring nearby, we selected all of the points for which the population count was above 50, and the distance to the nearest monitor above 16 kilometers. We then created a new point layer out of this selection.

3.3.3 Assembling air quality readings

Identifying Nearby Monitors

We chose to collect $PM_{2.5}$ concentration data from all monitors and sensors within 16 kilometers (16.1 km) of our set of 2019 prescribed burns. It is certainly possible for smoke to travel farther than 16 kilometers from a burn site, depending on the size of the burn, the weather conditions, and other factors. However, concentrations of pollutants such as $PM_{2.5}$ are often highest closest to the burn (Robinson, et al 1994; Liu, 2009; Price et al, 2016). There is not a consensus on the average distance that smoke or pollutants within smoke can travel from the burn site. Selecting a range too large risks including air quality impacts unrelated to prescribed burning; too small risks excluding monitors that could provide relevant data. The Forest Service notes that consistent winds can push smoke 16 kilometers, or possibly further, while DNR limits burning within five miles (8 kilometers) of communities, implying that smoke and air quality impacts are most significant within a five mile radius (National Wildfire Coordinating Group, 2001; Washington DNR, 2019a). For the purpose of this research we were not able to model individual smoke plumes from each 2019 prescribed burn, and so determined a radius of 16 kilometers around each burn was reasonable to conduct our analysis.

To understand which monitors fell within 16 kilometers of a burn, we used the buffer tool to create a 10 mile buffer around each burn. 30 of the 2019 prescribed burns did not have a sensor or monitor within 16 kilometers of the burn location.

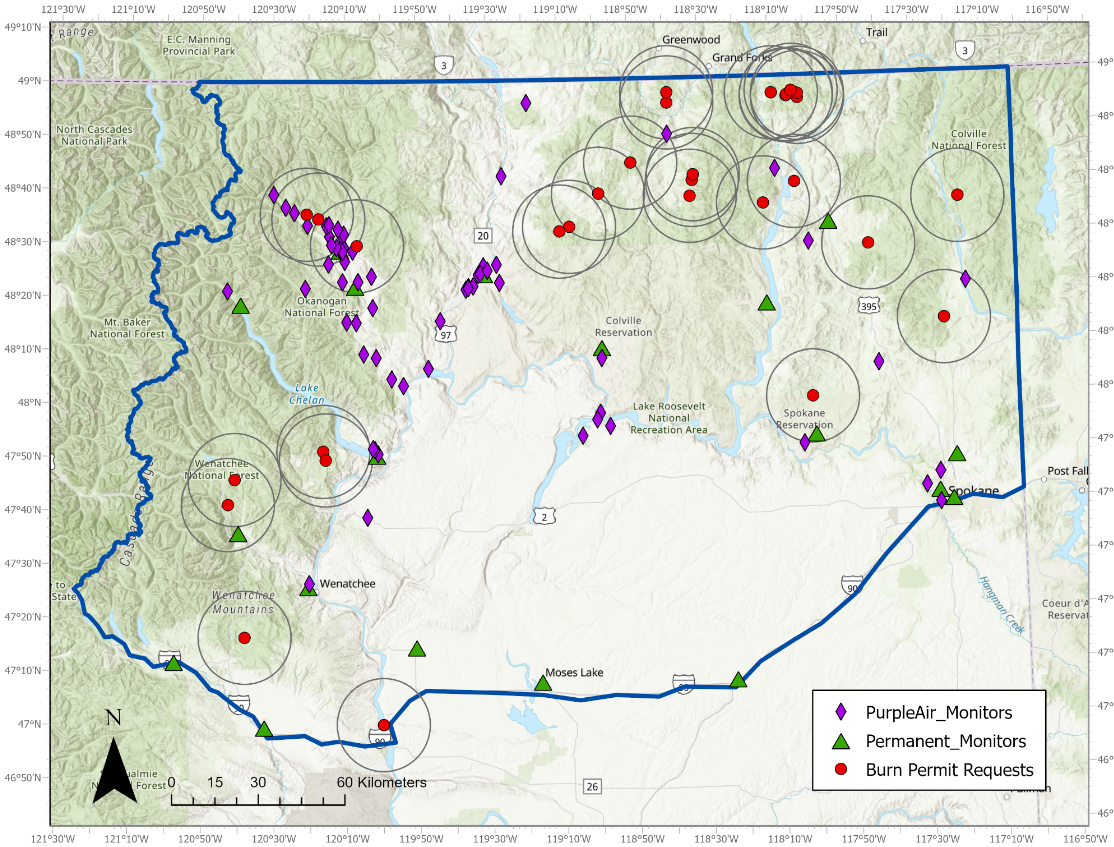
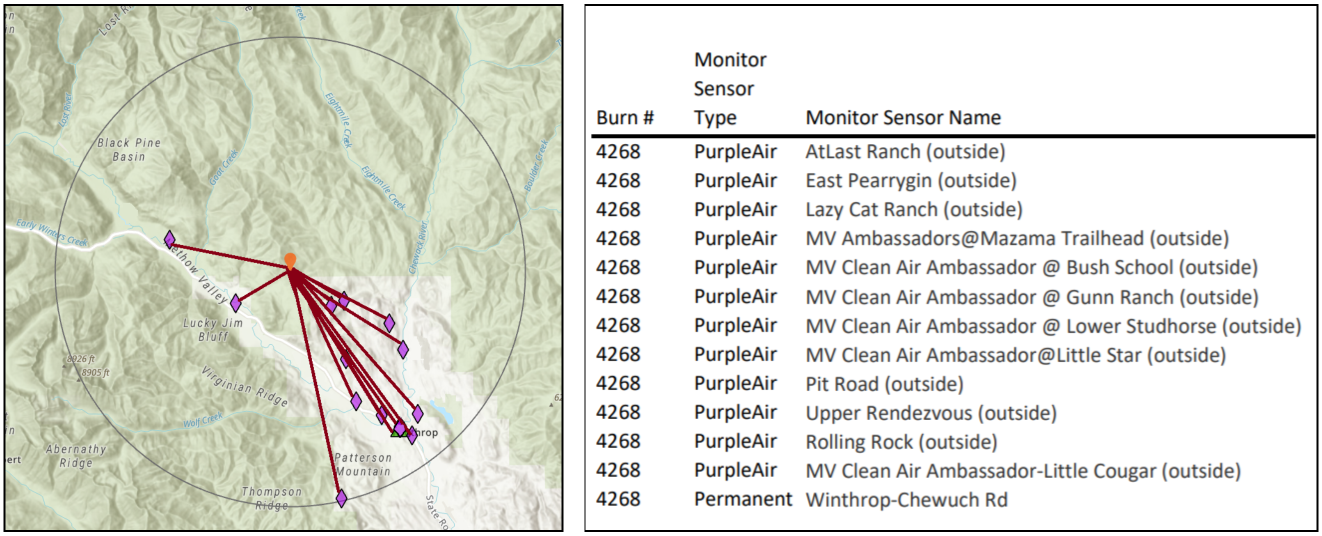


Figure 11. Map showing the ten mile buffer zones around each 2019 prescribed burn, along with permanent monitors and PurpleAir monitors.

Next, working in ArcGis, we used the 10 mile buffer layer to clip the sensors and monitors layer, resulting in a feature layer containing only monitors and sensors within 16 kilometers of a burn. We then used a spatial join to create a dataset that treated each burn and nearby monitor/sensor combination as unique data point. This dataset, “Dataset 1” can be viewed in Appendix II. Figure 11 gives a simplified example of a spatial join and the resulting dataset: doing a one-to-many spatial join of this 2019 prescribed burn near Winthrop, Washington would result in a dataset with 13 rows of data, because there are 12 PurpleAir monitors and one permanent monitor within 16 kilometers of this burn.



Burn #	Monitor Sensor Type	Monitor Sensor Name
4268	PurpleAir	AtLast Ranch (outside)
4268	PurpleAir	East Pearrygin (outside)
4268	PurpleAir	Lazy Cat Ranch (outside)
4268	PurpleAir	MV Ambassadors@Mazama Trailhead (outside)
4268	PurpleAir	MV Clean Air Ambassador @ Bush School (outside)
4268	PurpleAir	MV Clean Air Ambassador @ Gunn Ranch (outside)
4268	PurpleAir	MV Clean Air Ambassador @ Lower Studhorse (outside)
4268	PurpleAir	MV Clean Air Ambassador@Little Star (outside)
4268	PurpleAir	Pit Road (outside)
4268	PurpleAir	Upper Rendezvous (outside)
4268	PurpleAir	Rolling Rock (outside)
4268	PurpleAir	MV Clean Air Ambassador-Little Cougar (outside)
4268	Permanent	Winthrop-Chewuch Rd

Figure 12. An example illustrating how a one-to-many spatial join of 2019 prescribed burns to monitors and sensors within 16 kilometers, and the resulting dataset. The lines connecting the prescribed burn and the monitors and sensors are for illustrative purposes only (they are not actually shown in ArcGIS during the spatial join). They are meant to show how each row in the resulting dataset is determined.

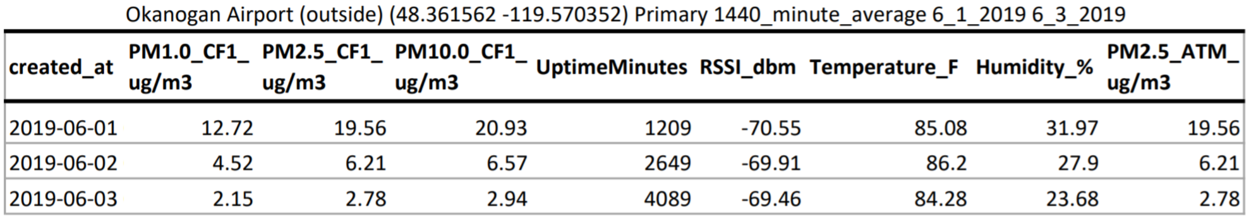
Adding in Permanent Monitor Data

To Dataset 1 we added in all 24-hour average $PM_{2.5}$ observations for every permanent monitor within 16 kilometers of a burn on the day of each burn. According to the PWFSLSmoke data, all of the permanent monitors in the study area were in operation at the time of the burn.

Adding in PurpleAir Sensor Data

We used the PurpleAir Sensor Data Download Tool to download 24-hour average $PM_{2.5}$ $\mu g/m^3$ observations for every PurpleAir sensor within 16 kilometers of a burn, on the day of each burn. Each PurpleAir sensor records data from two laser particle counters, identified as Laser A and Laser B. The dual laser particle counters are intended to provide a level of data integrity (PurpleAir Inc., 2021). If readings from the two counters are not within close agreement, the sensor is automatically flagged or downgraded (marked as faulty) (PurpleAir Inc., 2021). A laser counter may become faulty due to fan failure, insects or other debris inside the device or dust accumulation from long term exposure (Purple Air, Inc. 2021).

The Sensor Data Download Tool allows file downloads of individual data recorded by each laser particle counter belonging to a particular sensor. When using the tool, users can specify the time period for which they would like to download data. Each downloaded data file (a comma separated values file) contains air quality and atmospheric information recorded by a laser particle counter within the specified time period. Table 1 below shows an example of such a file download for a single sensor's Laser A 24-hour average readings between June 1, 2019 and June 3, 2019.



Okanogan Airport (outside) (48.361562 -119.570352) Primary 1440_minute_average 6_1_2019 6_3_2019

created_at	PM1.0_CF1_ ug/m3	PM2.5_CF1_ ug/m3	PM10.0_CF1_ ug/m3	UptimeMinutes	RSSI_dbm	Temperature_F	Humidity_%	PM2.5_ATM_ ug/m3
2019-06-01	12.72	19.56	20.93	1209	-70.55	85.08	31.97	19.56
2019-06-02	4.52	6.21	6.57	2649	-69.91	86.2	27.9	6.21
2019-06-03	2.15	2.78	2.94	4089	-69.46	84.28	23.68	2.78

Table 1. Example data contained within a file generated using the PurpleAir Sensor Data Download Tool. In this case, the file contains 24-hour average readings between June 1, 2019 and June 3, 2019. $PM_{2.5}$ ATM value

For every day on which there was a prescribed burn in 2019, we downloaded the 24-hour average readings from both laser particle counters in every sensor within 16 kilometers of a burn. We then averaged the $PM_{2.5}$ ATM concentrations from both sensors to obtain a final value for 24-hour average $PM_{2.5}$ concentration in µg/m^3 for every nearby sensor on the day of a burn.[4,5] These values were added to Dataset 1.

---

[4] $PM_{2.5}$ concentration values shown on the PurpleAir map are also derived from an average of the $PM_{2.5}$ ATM value from both laser counters in a sensor.

[5] The mean percent difference between the two laser sensors for the observations we collected was 16%, while the median was 8%.

Assessing Burns with Worse than "Moderate" Air Quality Readings

We categorized the $PM_{2.5}$ concentration data according to the U.S. Air Quality Index.[6] Three burns had monitors or sensors within 16 kilometers register 24-hour average concentrations of PM2.5 that were worse than "Moderate" on the U.S. Air Quality Index (above the NAAQS maximum for $PM_{2.5}$, 35.5 µg/m^3). For these burns, we collected the hourly $PM_{2.5}$ readings for the 24-hour period following the burn (the burn time was not included in the dataset of burn permit requests from DNR, but it was available on DNR's online Burn Calendar at https://burnportal.dnr.wa.gov/calendar.

3.4 Identifying "no data" burns

Eight out of 60 prescribed burns were within 16 kilometers of just one low-cost PurpleAir sensor at the time of the burn, but the sensor was not recording $PM_{2.5}$ concentrations on the day of the burn. We do not have information as to why an individual sensor may not have been recording at the time of the burn. For the purpose of this analysis, we consider those burns with non-working sensors nearby together with burns that had zero sensors or monitors within 16 kilometers, since we do not have any $PM_{2.5}$ data for either sets. These are the "no data" burns. In total, there were 38 out of 60 prescribed burns in 2019 that did not have any air quality data from sensors or monitors within 16 kilometers. Figure 13 displays all 2019 prescribed burns, colored according to whether there was air quality monitor or sensor data available on the day of the burn, within 16 kilometers.

---

[6] The U.S. Air Quality Index for $PM_{2.5}$ is divided into six categories, with each category representing a different level of health concern. The index converts concentration of $PM_{2.5}$ in µg/m^3 into a scale from 0 to 500 (see Appendix I). For consistency, in this paper we use only $PM_{2.5}$ concentration and the associated level of health concern.

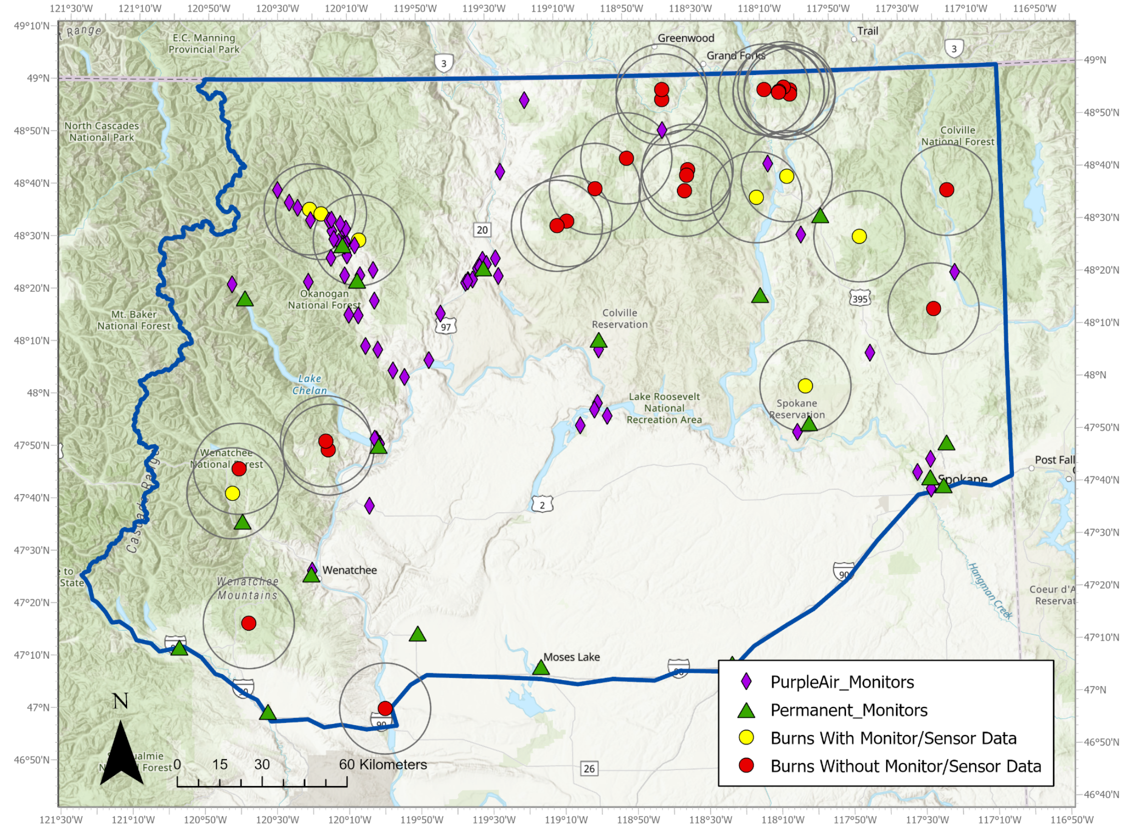


Figure 13. Map displaying 2019 prescribed burns, 10 mile buffer zones around each burn, and monitors and sensors in the study area. Dark red points denote burns that had at least one working monitor or sensor within 16 kilometers of the burn on the day of the burn (air quality data available). Yellow points denote burns that did not have at least one working monitor or sensor within 16 kilometers of the burn on the day of the burn (no air quality data available).

3.5 Estimating population near burns

3.5.1 Total population near all 2019 burns

To estimate the population potentially exposed to $PM_{2.5}$ from nearby burns, we then calculated the total population within 16 kilometers of each burn, in ArcGIS. The population totals range from 323 people within 16 kilometers of a burn 32 kilometers northeast of Omak, to 9,372 people within 16 kilometers of a burn near Colville. In total, 21,635 people lived within 16 kilometers of at least one 2019 prescribed burn.

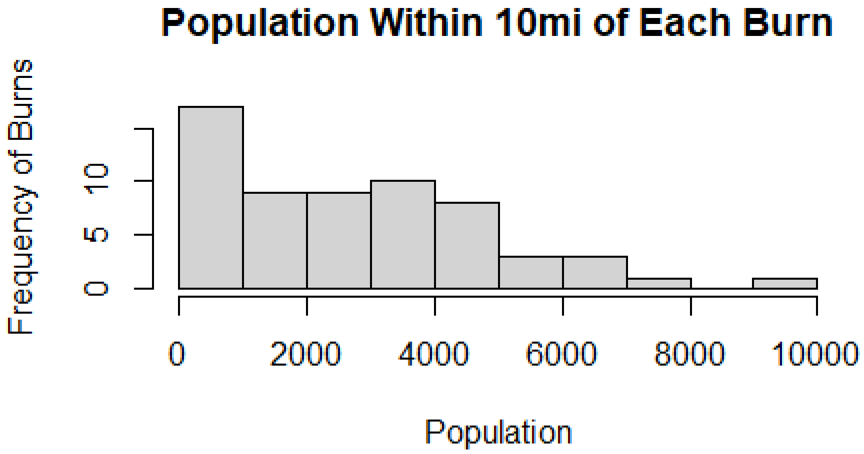


Figure 14. Histogram showing the distribution of counts of total population within 16 kilometers of a 2019 prescribed burn.

3.5.2 Population near burns without monitors or sensors nearby

To estimate the total number of people living near burns for which there was no data from nearby air quality monitors or sensors, we created a separate layer for those burns using the Select By Attributes tool in ArcGIS. We then used the buffer tool to create a 10 mile buffer around every one of those burns, with boundaries between buffers dissolved. This created several “no data” zones around certain burns. We then used the Zonal Statistics tool in ArcGIS to estimate the total ambient population within these zones in 2019.

4. RESULTS

4.1 Overview

Using our datasets, we evaluated the potential impact of our set of 2019 prescribed burns on the air quality of nearby populations. We compare 24-hour average $PM_{2.5}$ concentrations to the $PM_{2.5}$ Air Quality Index and its equivalent concentrations (see Appendix I). Because we relied on permanent regulatory monitors and low-cost air quality sensors, we were only able to evaluate the air quality impacts in areas where sensors or monitors existed. In the Methow Valley, monitors and sensors are widely distributed and generally placed where people live (see Figure 9 in Section 4.2). However, other areas where there were burns did not have any monitors or sensors nearby (within 16 kilometers), or had very few monitors or sensors. This prompted further inquiry into how well the monitor and sensor network is placed relative to ambient populations (where people commute, work, recreate, and live).

4.2 Spatial distribution of monitors and sensors

To begin to answer the question, “In 2019, did prescribed burning in eastern and central Washington expose populations near the burns to unhealthy concentrations of $PM_{2.5}$?” we first explored the distribution of permanent monitors and PurpleAir sensors in our study area, and their placements relative to population centers.[7] The map below shows the distribution of permanent monitors and PurpleAir sensors, against a $1km^2$ grid of population counts.

---

[7] Our population dataset provided the estimated total count of people within each $1km^2$ area in our study area. However our spatial analysis required us to measure the distance to the nearest monitor or sensor from the centerpoint of each $1km^2$ cell.

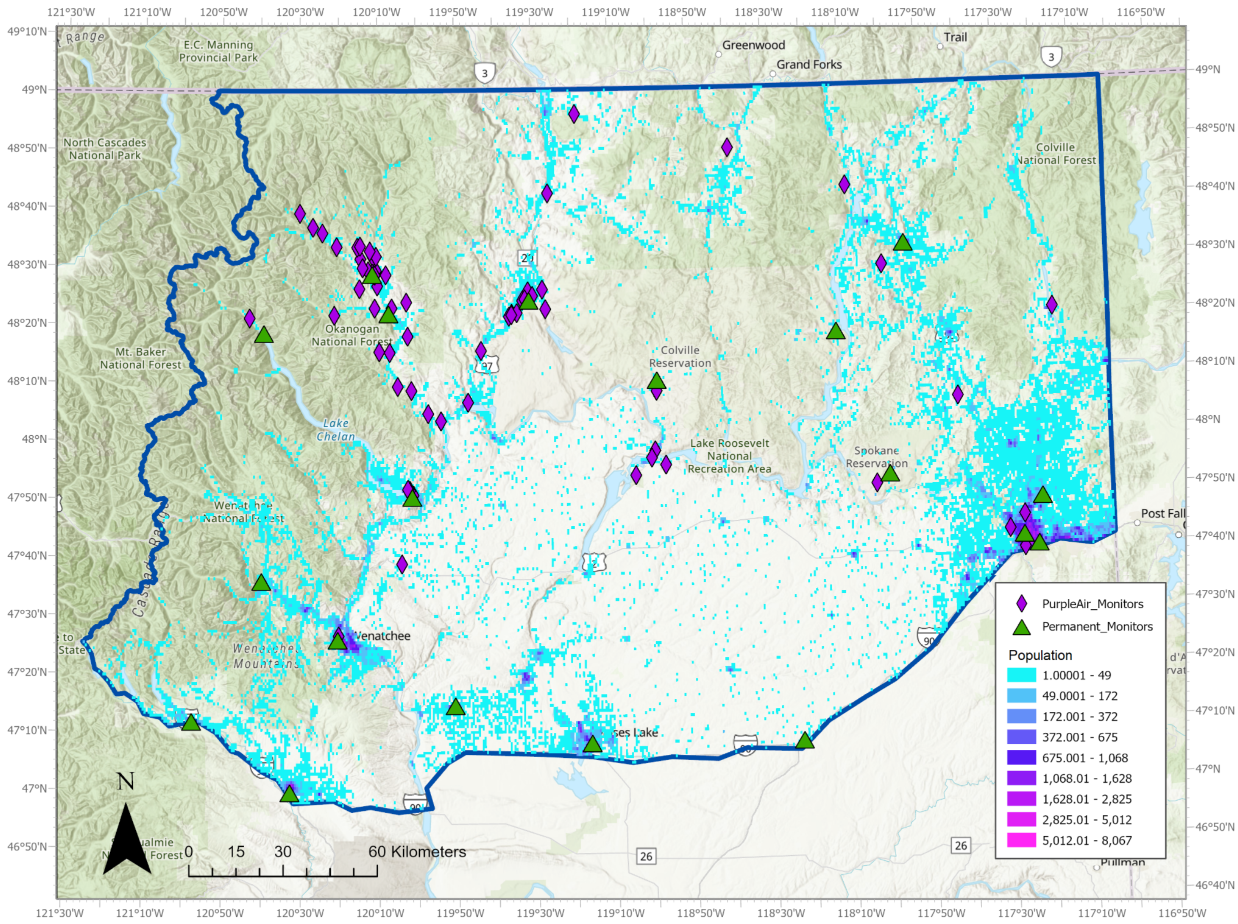


Figure 15. Map showing the locations of permanent regulatory monitors and PurpleAir sensors relative to population.

The range of distance to a monitor or sensor from a populated point within the study area was 0.08 kilometers to 64.5 kilometers, with a median of 13.3 kilometers. The chart below displays the distribution of distances from each point to the nearest monitor or sensor.

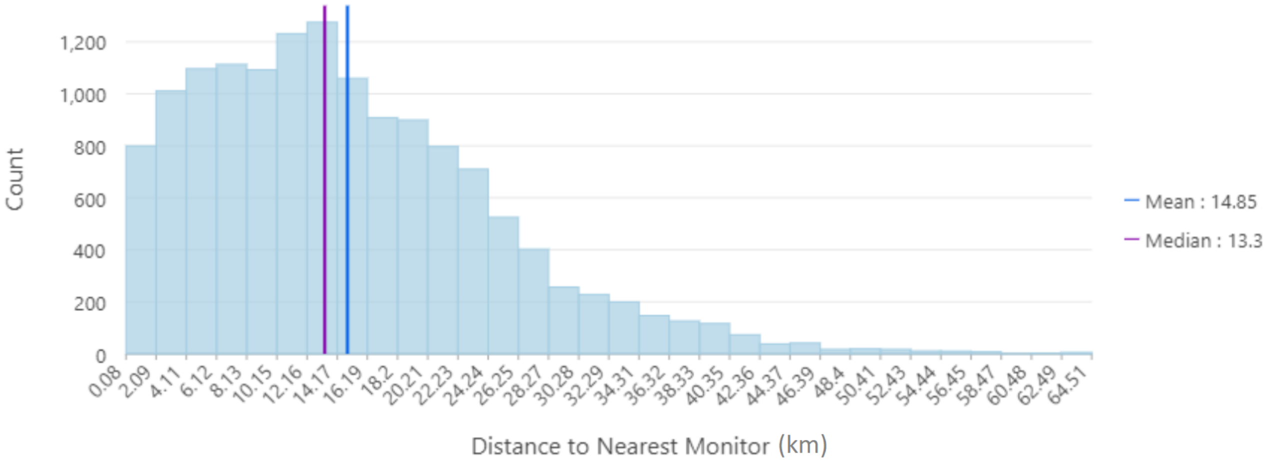


Figure 16. Histogram showing the distribution of distance to the nearest monitor or sensor for every populated centerpoint of the study area. The blue vertical line indicates the mean (14.8 kilometers), and the purple vertical line indicates the median.

The following map illustrates the relationship between the distance to the nearest monitor or sensor and the population count of every populated point in our study area, using bivariate coloring. The dark purple areas are places where there is both a higher population count (relative to the rest of the populated points) and air quality monitors or sensors are farther away.

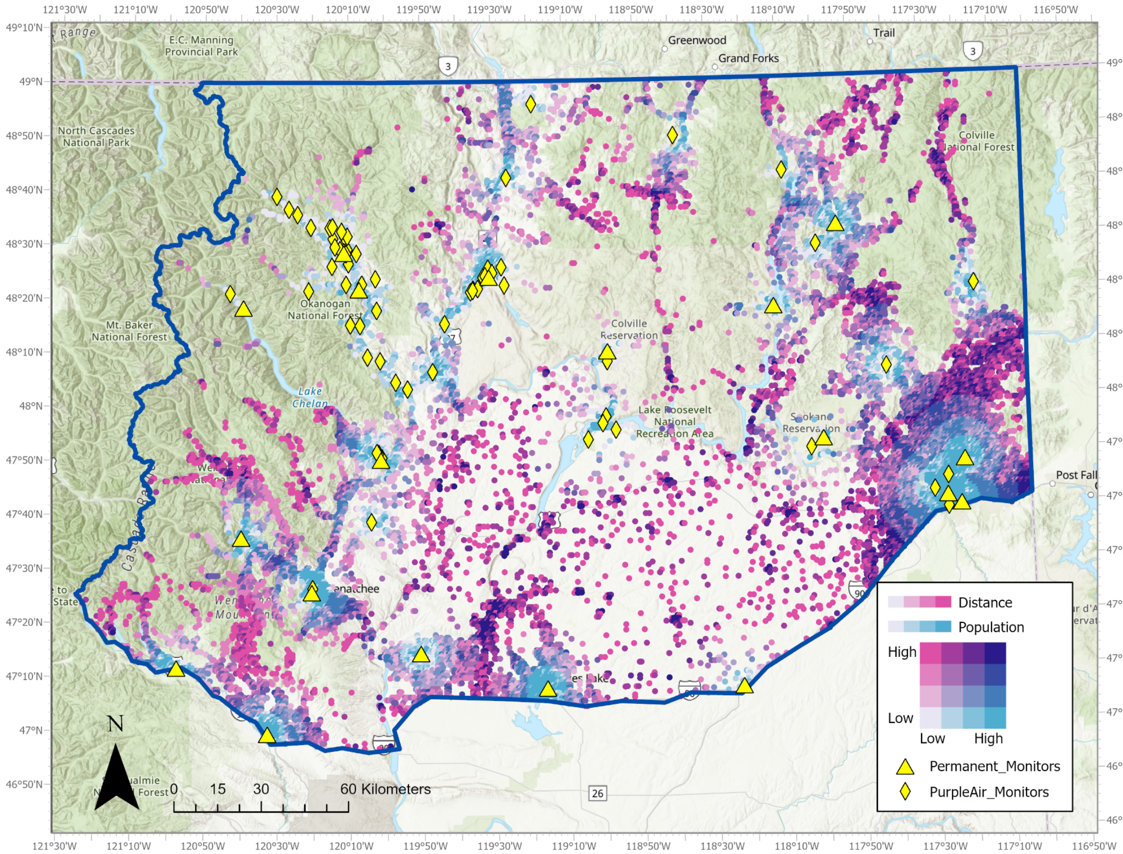


Figure 17. Map of study area showing population relative to distance to the nearest air quality monitor or sensor. Each point on the map is at the center of a 1km^2 grid area in which there was at least one person in 2019 (according to Landscan's ambient population data). The color of the point indicates the population within that 1km^2 area and the distance of that point to the nearest monitor or sensor. The dark purple points represent areas where the population is high relative to other points in the study area, and where the distance to the nearest monitor is farther relative to other points in the study area. Monitors and sensors are shown in yellow, for contrast.

281 points on our map had a population above 50 within the 1 km^2 area represented by the point and were more than ten 16 kilometers from the nearest permanent monitor or purple air sensor. Those points are shown on the map below with nearby cities labeled. Note that permanent monitors and purple air sensors just outside of the study area were not captured in this analysis, so points on the map near the edge of the study area may in fact be within 16 kilometers of a monitor or sensor outside the boundary of the study area.

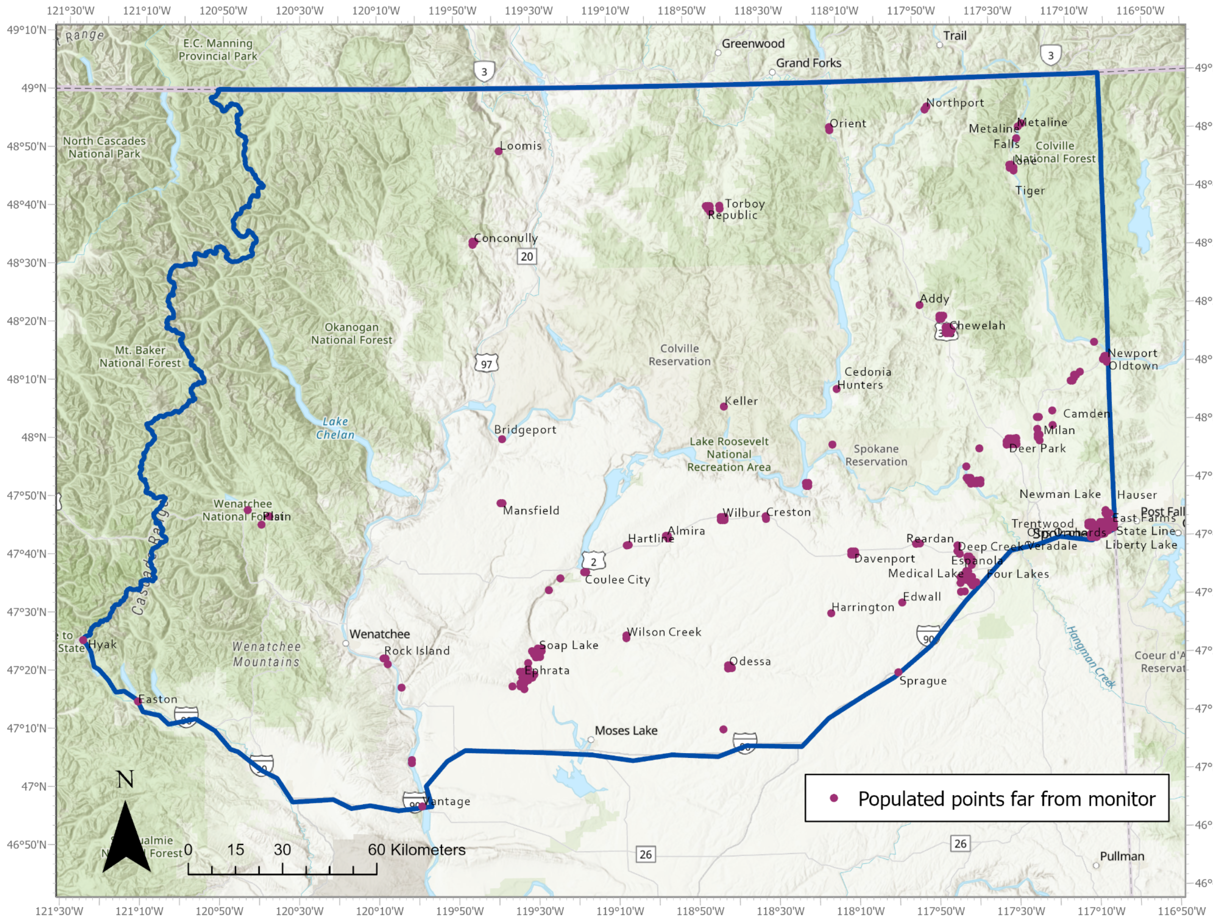


Figure 18. Map showing points in the study area that are greater than 16 kilometers from the nearest sensor or monitor and have an ambient population above 50 people.

4.3 Burns without air quality monitoring within 16 kilometers

For 38 of our 60 prescribed burns in 2019, there was no observed $PM_{2.5}$ concentration data from monitors or sensors within 16 kilometers because there was no monitor or sensor within 16 kilometers. These burn operations reported a total of 43,264 tons (39,249 megagrams) of biomass burned between April 16, 2019 and October 15, 2019. An estimated total ambient population of 19,816 people lived within 16 kilometers of these burns. These 38 burns are effectively excluded from further analysis of air quality impacts due to a lack of data.

4.4 Burns with monitoring within 16 kilometers

4.4.1 Potential air quality impacts of smoke from prescribed burns

There were 22 prescribed burns in 2019 with at least one working monitor or sensor within 16 kilometers. Burn managers reported a total of 10,043 tons (9,110 megagrams) of biomass burned during these burns.

In total, there were 75 monitors and sensors near those burns, so we collected 75 24-hour average $PM_{2.5}$ observations from the day of the burns. A total of 75 readings were collected, the bulk of which were from sensors near a set of 8 burns near Winthrop and Twisp. Readings ranged from concentrations of 0 to 130.5 $PM_{2.5}$ μg/m^3 with a mean of 15.3 μg/m^3 and a standard deviation of 18 μg/m^3. The readings are shown in Figure 19.

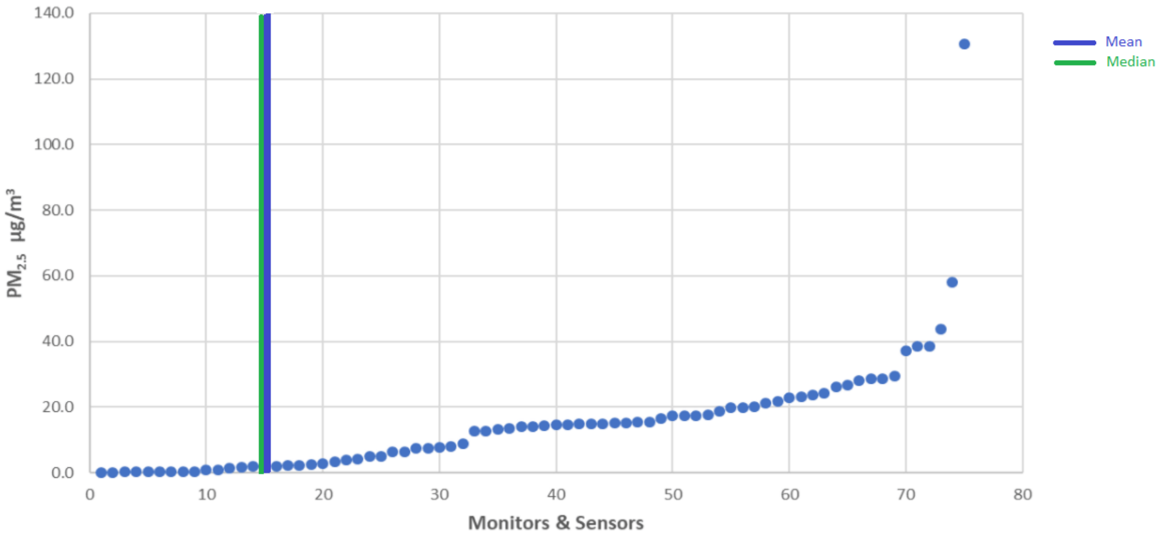
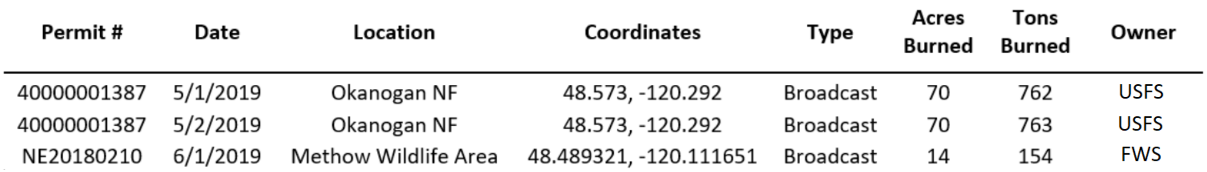


Figure 19. All 24-hour average $PM_{2.5}$ concentrations in μg/m^3 collected from monitors or sensors within 16 kilometers of a prescribed burn, on the day of the burn. The concentrations are displayed from least to greatest, with a range of 0 to 130.5 μg/m^3, a mean of 15.3 μg/m^3, a median of 14.2 μg/m^3, and a standard deviation of 18 μg/m^3.

There were three prescribed burns for which a monitor or sensor registered a 24-hour $PM_{2.5}$ concentration above the NAAQS maximum (greater than 35.5 $\mu g/m^3$) on the day of the burn. All three burns took place in the Methow Valley near Winthrop. Two of the burns were in the same location, on consecutive days. Table 2 outlines some of the administrative characteristics of these three burns.



Permit #	Date	Location	Coordinates	Type	Acres Burned	Tons Burned	Owner
40000001387	5/1/2019	Okanogan NF	48.573, -120.292	Broadcast	70	762	USFS
40000001387	5/2/2019	Okanogan NF	48.573, -120.292	Broadcast	70	763	USFS
NE20180210	6/1/2019	Methow Wildlife Area	48.489321, -120.111651	Broadcast	14	154	FWS

Table 2. Administrative characteristics of the three prescribed burns for which nearby monitors and sensors registered 24-hour $PM_{2.5}$ above NAAQS maximum. The two burns on the Okanogan National Forest were managed by the U.S. Forest Service, while the burn in Methow Wildlife Area was managed by the U.S. Fish and Wildlife Service.

We examined hourly air quality readings from monitors and sensors within 16 kilometers of these burns to understand the air quality levels prior to the burns. Hourly air quality can be evaluated along the EPA's Air Quality Index scale of "Good" to "Hazardous" (see Appendix I). The $PM_{2.5}$ concentrations recorded by nearby monitors in the hours preceding and following the two burns on May 1-2, 2019 are shown in the graph below. The National Ambient Air Quality Standards maximum 24-hour average $PM_{2.5}$ (35.5 $\mu g/m^3$) is indicated by the horizontal red line.

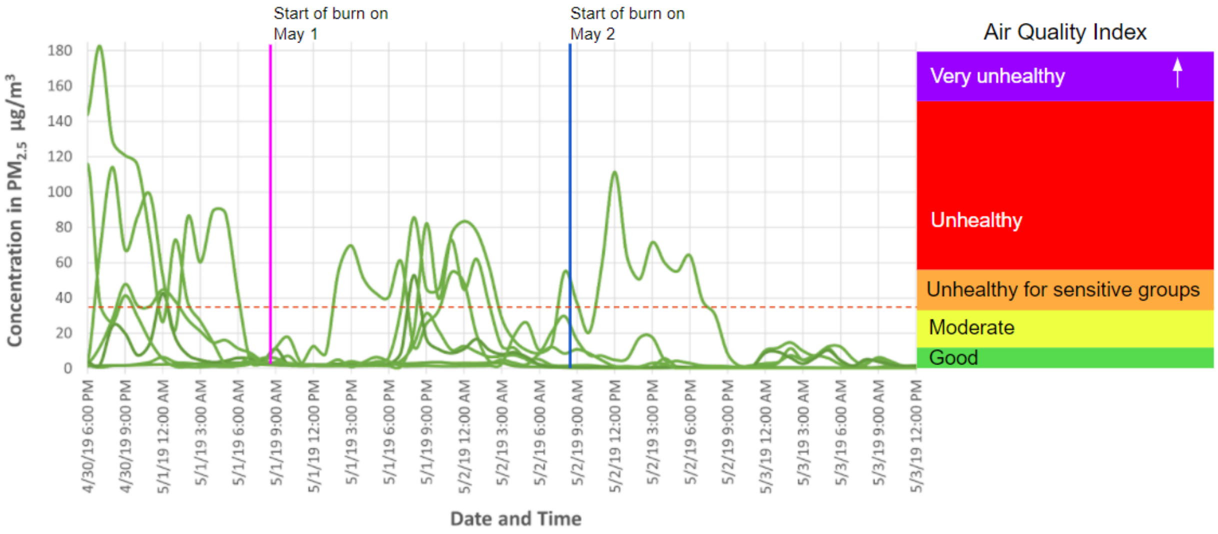


Figure 20. Hourly average concentrations of $PM_{2.5}$ in µg/m^3 registered by eight PurpleAir sensors in the Methow Valley area near the May 1 and May 2, 2019 burns. Each green line shows the $PM_{2.5}$ concentration registered by a particular sensor over time. The red dotted horizontal line indicates the maximum $PM_{2.5}$ concentration set by the EPA in the NAAQS, which is 35.5 µg/m^3. The Air Quality Index is shown on the right. The colors moving up from green to purple represent increasing levels of health concern.

Air quality was already worse than “Good” (greater than 12 µg/m^3) for a few hours prior to the start of the first burn, on May 1, 2019. A few sensors were already registering hourly average concentrations of $PM_{2.5}$ in the “Unhealthy for sensitive groups,” “Unhealthy,” and “Hazardous” ranges (above 55.5 µg/m^3) prior to the first burn on May 1, 2019. At least one sensor in the area registered hourly average $PM_{2.5}$ concentrations in the “Unhealthy” range (above 150.5 µg/m^3) for 13 of the 14 hours prior to the time of ignition of the first burn (6:30pm PST on April 30th to 8:30am PST on May 1st). By the time the prescribed burn on May 1st was ignited, all of the sensors in the area were registering hourly average $PM_{2.5}$ concentrations in the “Good” AQI range (below 12.5 µg/m^3). Air quality remained in the “Good” or “Moderate” range for all sensors until 2pm in the afternoon on May 1st, when one sensor began registering $PM_{2.5}$ concentrations in the “Unhealthy for Sensitive Groups” range. Five sensors in the area continued to record hourly average concentrations in the “Unhealthy for Sensitive Groups” range or in the “Unhealthy” range until 3am the following morning (on May 2, 2019). After ignition at 8:30am on May 2nd of the second burn, one sensor recorded hourly average concentrations in the “Unhealthy for Sensitive Groups” and the “Unhealthy” range for the next 11 hours. All other sensors recorded concentrations in the “Good” or “Moderate” ranges. Air quality observations from all monitors remained at “Moderate” or “Good” until the morning of May 4th, two days after the second burn.

The $PM_{2.5}$ concentrations recorded by nearby monitors in the hours preceding and following the burn on June 1, 2019 are shown in the graph on the next page.

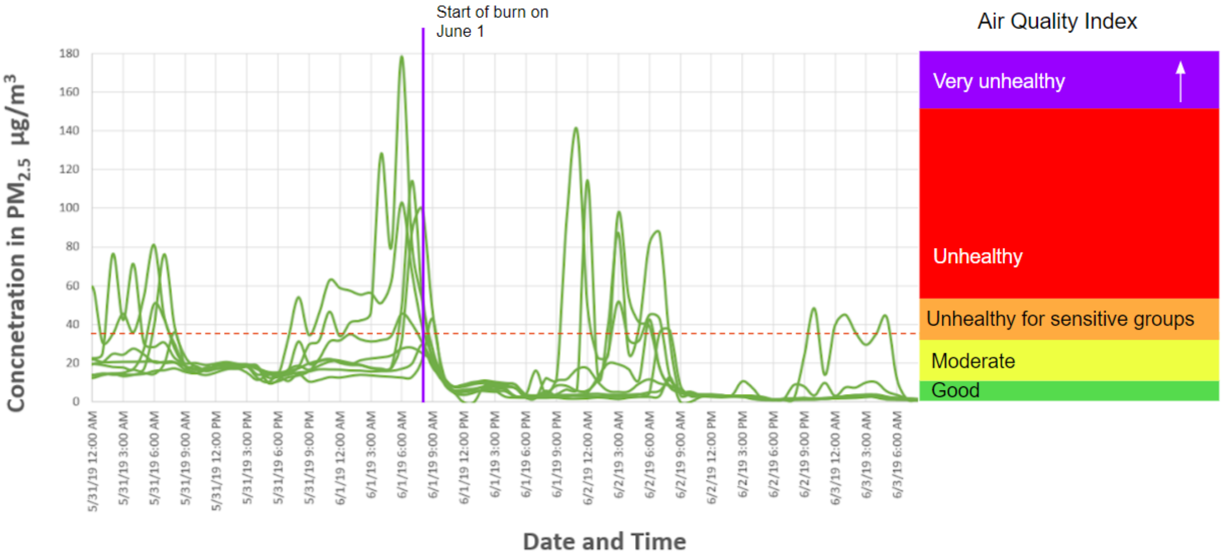


Figure 21. Hourly average concentrations of $PM_{2.5}$ in µg/m^3 registered by eight PurpleAir sensors in the Methow Valley area near the June 1, 2019 burns. Each green line shows the $PM_{2.5}$ concentration registered by a particular sensor over time. The red dotted horizontal line indicates the maximum $PM_{2.5}$ concentration set by the EPA in the NAAQS, which is 35.5 µg/m^3. The Air Quality Index is shown on the right. The colors moving up from green to purple represent increasing levels of health concern.

For 12 hours prior to ignition of the June 1st burn at 8:30am, five out of eight sensors in the region had been recording hourly average $PM_{2.5}$ concentrations between “Unhealthy for Sensitive Groups” and “Hazardous” (above 55.5 µg/m^3). Concentrations then fell to within the

“Good” range (below 12 μg/m^3) from 10:00am until 9:00pm on the day of the burn, which was ignited at 8:00am. Then, overnight between 9:00pm on June 1st and 8:00am on June 2nd, sensors recorded hourly average $PM_{2.5}$ concentrations between “Unhealthy for Sensitive Groups” and “Unhealthy” for 10 of 11 hours. For the following two days, one sensor registered hour concentrations in the “Unhealthy for Sensitive Groups" range for up to four hours overnight; otherwise all sensors registered concentrations in the “Good” or “Moderate” range.

4.4.2 Potential population exposed to unhealthy air quality

An estimated 244 people within 16 kilometers of the burns on May 1-2, 2019 may have been exposed to at least two days of 24-hour average $PM_{2.5}$ concentrations above the NAAQS maximum. An estimated 2,270 people within 16 kilometers of the June 1, 2019 burn may have been exposed to 1 day of 24-hour average $PM_{2.5}$ concentrations above the NAAQS maximum. Further, an estimated 1,411 people were within 16 kilometers of all three burns, and thus may have experienced three days of 24-hour average $PM_{2.5}$ concentrations above the NAAQS maximum.

5. DISCUSSION

5.1 Coverage of the air quality sensor & monitor network

In the process of evaluating the air quality impacts of prescribed burning in the study area, we inevitably evaluated the network of air quality monitoring and sensors as well. We found that permanent regulatory air quality monitors are few and far between in central and northeastern Washington, with only 23 monitors distributed across the 59,735 square kilometer area used for this study. The addition of 67 low-cost PurpleAir sensors expands the area for which there is air quality monitoring. Low-cost sensors have been shown to provide reliable and accurate $PM_{2.5}$ observations when the correct conversion is applied (Tryner et al, 2020). However, even with the PurpleAir sensor network, significant gaps in the air quality monitoring network remain.

Due to the limited air quality sensor and monitor network in 2019 (23 permanent regulatory monitors and 67 outdoor PurpleAir sensors), this study was limited to examining the observed air quality impacts of only 22 broadcast burns. The other 38 broadcast burns that would have been included in the study were more than 16 kilometers from an air quality monitor or sensor. While smoke from prescribed burning can travel more than 16 kilometers from a burn site, concentrations of pollutants such as $PM_{2.5}$ are often highest closest to the burn (Robinson, et al 1994; Liu, 2009; Price et al, 2016). Without monitors or sensors close to this set of 2019 prescribed burns, we could not examine their impacts to air quality. The excluded burns include the impact of burning 43,264 tons (39,249 megagrams) of biomass on the air quality of 19,816 people living within 16 kilometers of those burns. Thus, for the purpose of collecting monitoring data on smoke impacts from broadcast burns in 2019, the network of permanent monitors and PurpleAir sensors was not adequately distributed. Our analysis excluded pile burns and only examined burn impacts in 2019; therefore, it is possible that the locations of permanent monitors and PurpleAir sensors would be more advantageous in a study that examines several years of prescribed burning of all types.

However, since the purpose of air quality monitoring may be construed as providing data to support human healthy quality objectives, understanding locations of permanent monitors and

PurpleAir sensors relative to where *people* are, rather than where prescribed fires burn, may be a useful endeavor. Our analysis indicated there are several areas in central and northeastern Washington that do not have PurpleAir sensors or permanent monitors nearby, but are relatively densely populated. For the purpose of measuring air quality impacts from prescribed burns, or even air quality impacts from wildfires, these are populated areas that have no publicly available observed air quality data. For example, the unincorporated town of Plain sits just north of Leavenworth, Washington, within the edge of Okanogan-Wenatchee National Forest. In 2019, Plain had an average ambient population of 182 people. Plain is more than 19 kilometers from the nearest permanent monitor, and more than 48 kilometers from the nearest PurpleAir monitor, but was within 11 kilometers of two broadcast burns in 2019 (and potentially more burns not included in our study due to burn type or reported post-burn information). The town of Ione, Washington is surrounded on almost all sides by Colville National Forest. In 2019, it had an ambient population of at least 529 people, but no permanent monitors or PurpleAir sensors within 40 kilometers. Republic, Washington had a population of 1,182 in the 2019 census (Census Reporter, 2021). At least six broadcast burns took place to the west, north, and east of Republic in 2019, within 16 kilometers; yet, the closest monitor or sensor to Republic is 19 kilometers away.

Without publicly available air quality data, residents and visitors to these towns may not be able to ascertain when air quality conditions caused by prescribed burning or other sources of smoke, make certain activities unsafe. Additionally, a fragmented monitoring network hindered this study and will likely hinder future studies that rely on observed air quality data. Indeed, researchers have previously noted the spatial inadequacy of regulatory monitor networks to capture smoke impacts to air quality from prescribed burns, though they note the potential for low-cost sensor networks to provide supplemental data (Huang et al, 2021).

The distribution of permanent regulatory monitors and PurpleAir sensors relative to particular demographic trends is a significant area for future research. PurpleAir sensors are commonly referred to as ‘low-cost sensors’, in reference to the fact that they can be purchased at a cost of $250-$280 USD (PurpleAir Inc. 2021). However, these prices may still pose a financial barrier to individuals. A future research might ask whether income or wealth levels are different in populated areas where PurpleAir sensors are widespread, such as Winthrop, Washington, versus in populated areas where they are lacking, such as Republic, Washington.

Policymakers and public administrators may wish to prioritize the areas identified in this study that are more than 16 kilometers from a sensor and have an ambient population of more than 50 (see Figure 18) when deciding where to place another permanent regulatory monitor. Or, if budgetary constraints prevent the purchase, placement, and maintenance of widespread permanent regulatory monitors, community groups may turn to low-cost sensors like PurpleAir’s as a viable alternative. Community air monitoring networks that use PurpleAir sensors are not unprecedented. The extensive network of PurpleAir monitors that exists in the Methow Valley was established to help individuals reduce personal exposure to unhealthy air, protect sensitive populations, and provide data for air quality and environmental science (Durkin et al, 2020). In the short term, it would be prudent for public agencies, municipalities, and citizens’ groups in these towns to establish networks of low-cost sensors, such as the Clean Air Ambassador Program created by Clean Air Methow, or the Okanogan River Airshed Partnership. If the presence of real-time air quality information can change individual behavior such that even one life is saved, the cost of a PurpleAir sensor certainly pales in comparison to typical estimates of the value of a statistical life.[8]

5.2 Prescribed burns and nearby $PM_{2.5}$ concentrations

Our analysis sought to understand whether prescribed burns had an impact on the air quality of populated places nearby. We understood “impact” as monitors or sensors within 16 kilometers of the burns registering 24-hour average $PM_{2.5}$ concentrations above the National Ambient Air Quality Standards maximum following the burns. Sensor and monitor data was only able to be collected for 22 out of our initial set of 60 broadcast burns. Thus, the results of this analysis are constrained by a relatively small sample size.

24-hour average concentrations of $PM_{2.5}$ above the NAAQS maximum (above 35.5 $\mu g/m^3$) were registered by nearby monitors during and after three prescribed burns. In all three cases, hourly average concentrations above the NAAQS maximum were recorded by sensors prior to ignition of the burns, so it is difficult to conclude whether subsequent unhealthy $PM_{2.5}$ concentrations were the result of the three burns in our analysis, other sources of $PM_{2.5}$, or a combination thereof.

To estimate the total population potentially exposed to unhealthy air quality that may have been caused by these burns, we totaled the ambient population within 16 kilometers of each burn — in effect creating a circle with a radius of 16 kilometers, with the burn at the center. However, it is unlikely the smoke from these burns simply dissipated out from the burn locations in every direction; while prescribed burns tend to be conducted at times when wind speed is

---

[8] The EPA recommends using the estimate of USD $7.4 million in 2006 dollars for cost-benefit analyses “that seek to quantify mortality risk reduction benefits regardless of the age, income, or other population characteristics of the affected population.” (U.S. EPA, 2020) An outdoor PurpleAir sensor costs between USD $250 and $280 (PurpleAir Inc, 2021).

relatively low, even low winds can fine transport particulate matter several kilometers away (Robinson et al, 2011; Miller et al, 2019). As a result, the population exposed to smoke from a prescribed burn is more likely to be a "slice" of the area around a burn, so our estimates of people exposed to the three burns corresponding to high $PM_{2.5}$ concentrations above may be biased upward. At the same time, smoke from a burn may have travelled beyond 16 kilometers; since our estimates did not capture ambient populations more than 16 kilometers from a burn, for some burns we may have underestimated the true population exposed to unhealthy levels of $PM_{2.5}$. It is also possible the smoke travelled less far, and we over-included the population for any given burn. We can conclude that some people — those living near the PurpleAir sensors or permanent monitors that recorded high concentrations of $PM_{2.5}$ — were potentially exposed to up to three days of air quality above the NAAQS 24-hour maximum, during and after these three burns were ignited. Further research may incorporate smoke plume modeling to understand the likelihood that the unhealthy air was a result of these prescribed burns.

There were 19 prescribed burns for which monitors and sensors within 16 kilometers did not record $PM_{2.5}$ concentrations above the NAAQS 24-hour maximum on the days of the burns. From these, we conclude that smoke from those prescribed burns *did not* reach populations close to those monitors and sensors. For example, although the three burns north of the Methow Valley (discussed above) *did* have monitors and sensors nearby register 24-hour average concentrations above the NAAQS maximum on the days of the burns, five other burns in the same area did *not*. Populated areas in the Methow Valley are fairly well-covered by two permanent monitors and 26 PurpleAir sensors so it is unlikely 24-average concentrations of $PM_{2.5}$ above the NAAQs maximum reached or passed through these areas without any sensors or monitors reflecting as much. This suggests that most of the 2019 broadcast around the Methow Valley did *not* create smoke that exceeds maximum NAAQS levels for $PM_{2.5}$. For those burns, the guidelines set forth in Washington DNR's 1998 Smoke Management Plan for permitting prescribed burns, and the day-of prescribed burn "go - no go" decisions, seemed to have worked reasonably well to prevent immediate smoke intrusions into populated areas. It is also possible, though inconclusive based on these results, that prescribed burning typically does not have significant air quality impacts.

Of the 19 burns that did not have nearby monitors register $PM_{2.5}$ concentrations above the NAAQS maximum, most of these burns occurred in areas that were not well-covered by other monitors and sensors. This makes drawing direct conclusions from a single monitor and sensor risky. For example, the community of Wellpinit, Washington, located in the Spokane Reservation, has a permanent monitor at the Wellpinit Boys and Girls Club. That monitor registered a 24-hour average $PM_{2.5}$ concentration in the "Good" AQI range on May 1, 2019 and May 2, 2019, when two prescribed burns burned 100 acres 13 kilometers north of Wellpinit; so, we can conclude that the ambient population of over 1000 people within Wellpinit likely did not experience unhealthy concentrations of $PM_{2.5}$ as a result of that prescribed burn. However, we do not know whether the community around Springdale, Washington, which lies 21 kilometers east-northeast of the same May 1-2 burns, similarly experienced only good air quality during and after those burns, because there are no PurpleAir sensors or permanent monitors in or near Springdale. A future study may use smoke modeling to understand whether smoke from those burns may have exposed people in Springdale or other areas to days of $PM_{2.5}$ concentrations above the NAAQS maximum.

5.3 Data limitations, inconsistencies, and gaps

This study relied on three primary sources of data for its analysis: DNR's records of burn permit requests from 2003-2019, air quality data from PurpleAir monitors, and air quality data from permanent regulatory monitors. Several characteristics of DNR's burn permit requests may have influenced the results of our analysis. First, tribes such as the Spokane and the Confederated Tribes of the Colville Reservation regulate prescribed burning on reservation lands through tribal air quality agencies. Indeed, burning is a critical part of the Confederated Tribes of the Colville Reservation's Integrated Resource Management Plan (CCT, 2015). But because tribal prescribed burns are, for the most part, not included in Washington DNR's dataset of burn permit requests, our analysis does not capture any prescribed burning tribes may be doing.[9]

Second, the process by which we filtered all 2019 burn permit requests down to our final set of 60 may have added uncertainty to our results. To ensure we were examining prescribed burns that were completed, we excluded from our analysis 44 broadcast that did not include reported acres or tons burned in the burn permit request. However, it is possible that some of those burns *did* occur, but the fire managers or land managers responsible for the burns failed to report the burned tons and acres afterwards. Washington DNR's Smoke Management Plan (1998) requires that burns over 100 tons report post-burn data within 5 days of the burn; however, the extent to which this is enforced is not clear.

Third, the dataset of burn permit requests in DNR included several individual burns coded with the same permit number, that reported the same or similar number of tons or acres burned, in the same exact location, but occurred on different days. It was not clear at the time of

---

[9] Our analysis of 60 broadcast burns did include one burn on tribal lands - it is the burn discussed in section 5.2 near Wellpinit, Washington, in the Spokane Reservation.

this analysis whether some of those burns were accidental duplicate inclusions, or burns part of the same multi-day burning operation. DNR's Smoke Management Plan (1998) does not go into great detail about how permit numbers are allocated. It does state that, "Separate permits are required for each individual burn site," with an exception for multiple 'landings' burned by a single landowner. Additionally, the Plan outlines an approval process for multi-day burns, defined as "prescribed fire of any size conducted in eastern Washington for forest health purposes that cannot be managed so that the smoke will be fully dispersed by 12:00 p.m. on the day after the first ignition of the burn area" (Washington DNR, 1998). Thus, it is possible that burns in our dataset with the same permit number in the same location are multi-day burns approved under the same permit number; however, it remains unclear whether the reported acres and tons burned for each of these burns is the amount burned that day or the aggregated total from all of the days of burning under that permit number.

Finally, there were ten prescribed burn requests included in the set of 60 we examined for which there was *no* permit number recorded, even though the requests were marked as approved at the regional and the division level *and* the requests included post-burn information (acres and tons burned). It is unclear at present why those requests were not associated with a permit number, but worth noting in case the absence of a permit number indicates something particular about the burn.

6. CONCLUSION

It is well-established that prescribed burning is effective at reducing the risk of wildfire, and the smoke impacts associated with wildfire, and can improve ecosystem resilience and restore landscapes in the Pacific Northwest. (Pollet & Omi, 2002; Fernandes & Botelho, 2003; Stephens et al, 2012; Prichard & Kennedy, 2014). Despite the immense potential of prescribed burning to improve ecosystem functions and reduce the human, financial, and ecological risks of wildfires (Mitchell et al, 2009; Cochrane et al, 2012; Stevens et al, 2012; Calkin et al, 2014; Prichard et al, 2020), prescribed burning has seen a general decrease in use in the Northwestern United States since 1998 (Kolden, 2019). Eastern Washington in particular has experienced a decline in area burned through prescribed fire over the past two decades (Podschwit, 2021). Various factors may have contributed to this decline, including a lack of adequate capacity and funding to do prescribed burning (Schultz et al, 2019), and regulatory disincentives such as the exceptional events rule, which generally requires states to manage air quality from prescribed fire but *not* from wildfire. But one of the barriers to more prescribed burning — concerns about air quality impacts to humans, and the political hesitancy to support more prescribed burning that arises from those concerns — may be tackled with a better understanding of how smoke from prescribed burns is affecting air quality where people live, work, and recreate.

This analysis made an initial attempt at understanding the air quality impacts from prescribed burns in eastern Washington. Based on a relatively small set of broadcast burns conducted in 2019, we found few observed 24-hour $PM_{2.5}$ concentrations on the days of the burns that exceeded the maximum set by the NAAQS. A full accounting of the observed air quality impacts from prescribed burn for the past several years would show whether our finding of relatively little observed $PM_{2.5}$ impacts on air quality in some populated areas generally holds true for prescribed burning in Washington state.

If a full accounting of the impacts of prescribed burning on people's air quality could be made, an important opportunity for further research would be to study the tradeoffs of smoke impacts to air quality from a wildfire passing over an untreated area, from fuel treatments involving prescribed burning in the same area, and from wildfire passing over the same area after a prescribed burn. Since prescribed burning can mitigate the effects of future wildfires, and since wildfires tend to release more smoke than prescribed fires (Liu et al, 2017; Hyde et al, 2019), it follows that doing prescribed burning in an area at risk of high-severity wildfire may reduce overall $PM_{2.5}$ emissions in the long-term, even if some emissions occur in the short term as a result of the prescribed burning. Research that asks this question is not unprecedented. Schweizer et al (2018) noted that decades of fire suppression policy has created a "smoke emissions backlog"; their study used remote sensing of smoke plumes to measure smoke tradeoffs from prescribed fires and wildfires, and found that increased use of prescribed fire mitigates smoke exposure from both future wildfires and future prescribed fires, while fire suppression, "not only appears to shift the health burden of the emissions to a future date but also increases the intensity and number of people exposed in a single exposure." Recently, the EPA released a report comparing modeled air quality and public health impacts from prescribed fire and wildfire smoke. Their assessment, which looked at two case study fires, found that modeled $PM_{2.5}$ concentrations from prescribed burns were smaller and shorter in duration than those caused by wildfires (U.S. EPA, 2021a). The assessment also found the estimated total population exposure for prescribed burns was smaller than that for both hypothetical wildfire scenarios and actual fires examined in the study. To our knowledge, no such studies have been conducted in eastern Washington.

Increasing our understanding of air quality impacts from prescribed fires would be helpful for DNR, Ecology, and state officials tasked with overseeing prescribed burning. Moreover, DNR is seeking EPA approval of an update to Washington State's Smoke Management Plan. DNR must make the case that Washington State can manage air quality impacts from prescribed burning in a way that does not exceed the NAAQS. At the federal level, evidence that prescribed burning can be managed in a way that does not pose risks to human health, or that it can be used to mitigate greater *future* risks to human health from wildfires, could be beneficial in supporting regulatory action that corrects the perverse incentives that exist in the Clean Air Act.

In examining what permanent air monitors and low-cost sensors can tell us about prescribed burning impacts to air quality for a finite set of prescribed burns in eastern Washington, this study has taken a small step in that direction. Our findings show the network of permanent regulatory air quality monitors and PurpleAir low-cost sensors is inadequately distributed for measuring on-the-ground air quality impacts from prescribed burning, but in areas where monitors and sensors did exist near prescribed burns, air quality impacts were limited.

Fire and land managers and agencies cannot exercise their full potential to restore landscapes and protect people if emissions from prescribed burning are heavily regulated while wildfire emissions are exempted. Still, in order to increase prescribed burning in Washington, a full accounting of prescribed burn impacts to air quality and human health is needed. We hope this study will prompt further research on that front.

WORKS CITED

Afrin, S., & Garcia-Menendez, F. (2021). Potential impacts of prescribed fire smoke on public health and socially vulnerable populations in a Southeastern U.S. state. *The Science of the Total Environment, 794*, 148712.

Agee, J. (1993). *Fire ecology of Pacific Northwest forests.* Washington, D.C.: Island Press.

Agee, J., & Lolley, M. (2006). Thinning and Prescribed Fire Effects on Fuels and Potential Fire Behavior in an Eastern Cascades Forest, Washington, USA. *Fire Ecology, 2*(2), 3-19.

Aguilera, R., Corringham, T., Gershunov, A., & Benmarhnia, T. (2021). Wildfire smoke impacts respiratory health more than fine particles from other sources: Observational evidence from Southern California. *Nature Communications, 12*(1), 1493-8.

AirNow. (2021). *About AirNow.* https://www.airnow.gov/about-airnow/ (accessed November 7, 2021).

Baker, W. (2015). Are High-Severity Fires Burning at Much Higher Rates Recently than Historically in Dry-Forest Landscapes of the Western USA? *PloS One, 10*(9), E0136147.

Balch, J., Bradley, B., Abatzoglou, J., Nagy, R., Fusco, E., & Mahood, A. (2017). Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences - PNAS, 114*(11), 2946-2951.

Barbero, R., Abatzoglou, J., Larkin, N., Kolden, C., & Stocks, B. (2015). Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire, 24*(7), 892.

Barkjohn, K. K., Gantt, B. & Clements, A. L. (2021). Development and Application of a United States wide correction for PM2.5 data collected with the PurpleAir sensor. *Atmospheric Measurement Techniques*, 4(6), 4617-4637.

Boyd, R. (1999). *Indians, fire, and the land in the Pacific Northwest*. Corvallis, Oregon: Oregon State University Press.

Bracmort, K., & Library of Congress. Congressional Research Service, issuing body (Eds.). (2018). *Wildfire damages to homes and resources: Understanding causes and reducing losses.*

Calkin, D., Cohen, J., Finney, M., & Thompson, M. (2014). How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences - PNAS, 111*(2), 746-751.

Cattau, M., Wessman, C., Mahood, A., Balch, J., & Poulter, B. (2020). Anthropogenic and lightning‐started fires are becoming larger and more frequent over a longer season length in the U.S.A. *Global Ecology and Biogeography, 29*(4), 668-681.

CCT (Confederated Colville Tribes). (2015). Integrated Resource Management Plan 2015. Available online: https://www.colvilletribes.com/s/CTCR-2015-IRMP-online-2018-08-14.pdf

Census Reporter. (2021). Available online: https://censusreporter.org/ (accessed November 19, 2021).

Chi, R., Chen, C., Li, H., Pan, L., Zhao, B., Deng, F., & Guo, X. (2019). Different health effects of indoor‐ and outdoor‐originated PM2.5 on cardiopulmonary function in COPD patients and healthy elderly adults. *Indoor Air, 29*(2), 192-201.

Cochrane, M., Moran, C., Wimberly, M., Baer, A., Finney, M., Beckendorf, K., . . . Zhu, Z. (2012). Estimation of wildfire size and risk changes due to fuels treatments. *International Journal of Wildland Fire, 21*(4), 357.

Coop, J., Parks, S., Stevens-Rumann, C., Crausbay, S., Higuera, P., Hurteau, M., . . . Rodman, K. (2020). Wildfire-Driven Forest Conversion in Western North American Landscapes. *Bioscience, 70*(8), 659-673.

Cooper, T. (2019). *Smoke Management Plan Update Cover Memo*. Available online: https://www.dnr.wa.gov/publications/amp_sepa_other_smpupdate_cvr.pdf (accessed on November 27, 2021).

Durkin, A., Gonzalez, R., Isaksen, T., Walker, E., & Errett, N. (2020). Establishing a Community Air Monitoring Network in a Wildfire Smoke-Prone Rural Community: The Motivations, Experiences, Challenges, and Ideas of Clean Air Methow's Clean Air Ambassadors. *International Journal of Environmental Research and Public Health, 17*(22), 8393.

Dye, A., Kim, J., McEvoy, A., Fang, F., & Riley, K. (2021). Evaluating rural Pacific Northwest towns for wildfire evacuation vulnerability. *Natural Hazards (Dordrecht), 107*(1), 911-935.

Fan, J., Li, S., Fan, C., Bai, Z., & Yang, K. (2015). The impact of PM2.5 on asthma emergency department visits: A systematic review and meta-analysis. *Environmental Science and Pollution Research International, 23*(1), 843-850.

Fernandes, P., & Botelho, H. (2003). A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire, 12*(2), 117-128.

FLAME Act, H.R. 1404, 111th Cong. (2009). Available online: https://www.congress.gov/bill/111th-congress/house-bill/1404 (accessed on November 06, 2021).

Flesher, J. (2021, October 8). For Tribes, 'Good Fire' A Key to Restoring Nature and People. *The Associated Press*. Retrieved from https://apnews.com/article/science-business-forests-california-native-americans-eb2f25b2a932f707d4526bffb6cecf3e

Forest Service Report: Rising Firefighting Costs Raises Alarms. (2015). *Agriculture Department Documents and Publications,* Agriculture Department Documents and Publications, 2015-08-05.

Glickman, D., Babbitt, B., & U.S. Department of Agriculture. (2000). *Managing the impact of wildfires on communities and the environment: A report to the president in response to the wildfires of 2000.* Available online: https://www.doi.gov/sites/doi.gov/files/migrated/pmb/owf/upload/2000-Report-to-the-President.pdf (accessed November 3, 2021).

Halofsky, J., Peterson, D., & Harvey, B. (2020). Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology, 16*(1), Fire ecology, 2020-01-27, Vol.16 (1).

Hankins, M., & Zirkle, K. (2021). Washington State Smoke Management Plan Webinar. February 18, 2021. Available online: https://www.frames.gov/catalog/62912 (accessed on November 30, 2021).

Hansen, D. G., Carlson, J. E. & State of Washington Department of Ecology Air Quality Program. (2004). *Alternatives to Agricultural Burning: Agricultural Practices to Help Eliminate or Reduce the Need to Burn.* Available online: https://ecology.wa.gov/DOE/files/19/19cf8302-9490-4d03-b51a-0882d6597167.pdf (accessed November 22, 2021).

Haugo, R., Kellogg, B., Cansler, C., Kolden, C., Kemp, K., Robertson, J., . . . Restaino, C. (2019). The missing fire: Quantifying human exclusion of wildfire in Pacific Northwest forests, USA. *Ecosphere (Washington, D.C), 10*(4), N/a.

Healthy Forests Restoration Act of 2003, H.R. 1904, 108th Cong. (2003). Available online: https://www.govinfo.gov/content/pkg/BILLS-108hr1904enr/pdf/BILLS-108hr1904enr.pdf (accessed November 5, 2021).

Hessburg, P., Smith, B., Salter, R., Ottmar, R., & Alvarado, E. (2000). Recent changes (1930s–1990s) in spatial patterns of interior northwest forests, USA. *Forest Ecology and Management, 136*(1), 53-83.

Hoover, K. & Congressional Research Service. (2020). *Federal Wildfire Management: Ten-Year Funding Trends and Issues (FY2011-FY2020).*

Huang, R., Hu, Y., Russell, A., Mulholland, J., & Odman, M. (2019). The Impacts of Prescribed Fire on PM2.5 Air Quality and Human Health: Application to Asthma-Related Emergency Room Visits in Georgia, USA. *International Journal of Environmental Research and Public Health, 16*(13), 2312.

Huang, R., Lal, R., Qin, M., Hu, Y., Russell, A., Odman, M., . . . O'Neill, S. (2021). Application and evaluation of a low-cost PM sensor and data fusion with CMAQ simulations to quantify the impacts of prescribed burning on air quality in Southwestern Georgia, USA. *Journal of the Air & Waste Management Association* (1995), 71(7), 815-829.

Hyde, J., & Strand, E. (2019). Comparing Modeled Emissions from Wildfire and Prescribed Burning of Post-Thinning Fuel: A Case Study of the 2016 Pioneer Fire. *Fire (Basel, Switzerland), 2*(2), 22.

Jaffe, D., O'Neill, S., Larkin, N., Holder, A., Peterson, D., Halofsky, J., & Rappold, A. (2020). Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association (1995), 70*(6), 583-615.

Johnson Gaither, C., Afrin, S., Garcia-Menendez, F., Odman, M., Huang, R., Goodrick, S., & Ricardo da Silva, A. (2019). African American Exposure to Prescribed Fire Smoke in Georgia, USA. *International Journal of Environmental Research and Public Health, 16*(17), 3079.

Johnson, K., A. Holder, S. Frederick, & A. Clements. PurpleAir PM2.5 U.S. Correction and Performance During Smoke Events 4/2020. International Smoke Symposium, Raleigh, NC, April 20 - 24, 2020

Kolden, C. (2019). We’re Not Doing Enough Prescribed Fire in the Western United States to Mitigate Wildfire Risk. *Fire (Basel, Switzerland), 2*(2), 30.

Lake, F., Wright, V., Morgan, P., McFadzen, M., McWethy, D., & Stevens-Rumann, C. (2017). Returning Fire to the Land: Celebrating Traditional Knowledge and Fire. *Journal of Forestry, 115*(5), 343-353.

Littell, J., McKenzie, D., Peterson, D., & Westerling, A. (2009). Climate and Wildfire Area Burned in Western U.S. Ecoprovinces, 1916—2003. *Ecological Applications, 19*(4), 1003-1021.

Littell, J., Oneil, E., McKenzie, D., Hicke, J., Lutz, J., Norheim, R., & Elsner, M. (2010). Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change, 102*(1-2), 129-158.

Liu, Y., Goodrick, S., Achtemeier, G., Jackson, W., Qu, J., & Wang, W. (2009). Smoke incursions into urban areas: Simulation of a Georgia prescribed burn. *International Journal of Wildland Fire, 18*(3), 336.

Liu, J., Pereira, G., Uhl, S., Bravo, M., & Bell, M. (2015). A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environmental Research, 136*, 120-132.

Liu, X., Huey, L., Yokelson, R., Selimovic, V., Simpson, I., Müller, M., . . . Wolfe, G. (2017). Airborne measurements of western U.S. wildfire emissions: Comparison with prescribed burning and air quality implications. *Journal of Geophysical Research. Atmospheres, 122*(11), 6108-6129.

Liu, Y., Austin, E., Xiang, J., Gould, T., Larson, T., & Seto, E. (2021). Health Impact Assessment of the 2020 Washington State Wildfire Smoke Episode: Excess Health Burden Attributable to Increased PM2.5 Exposures and Potential Exposure Reductions. *Geohealth, 5*(5), E2020GH000359-N/a.

Long, J., & Lake, F. (2018). Escaping social-ecological traps through tribal stewardship on national forest lands in the Pacific Northwest, United States of America. *Ecology and Society, 23*(2), 10.

Long, J., Lake, F., & Goode, R. (2021). The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecology and Management, 500*, 119597.

Marks-Block, T., Lake, F., Bliege Bird, R., & Curran, L. (2021). Revitalized Karuk and Yurok cultural burning to enhance California hazelnut for basketweaving in northwestern California, USA. *Fire Ecology, 17*(1), Fire ecology, 2021-02-19, Vol.17 (1).

M. P. North, S. L. Stephens, B. M. Collins, J. K. Agee, G. Aplet, J. F. Franklin, & P. Z. Fulé. (2015). Reform forest fire management: Agency incentives undermine policy effectiveness. *Science (American Association for the Advancement of Science), 349*(6254), 1280-1281.

Mazama Science. (2020). *Introduction to PWFSLSmoke.* Available online https://cran.r-project.org/web/packages/PWFSLSmoke/vignettes/PWFSLSmoke.html (accessed on October 3, 2021).

Melvin, M.A. (2018). 2018 National Prescribed Fire Use Survey Report. *The National Association of State Foresters.* Available online: https://www.stateforesters.org/newsroom/2018-national-prescribed-fire-use-report/ (accessed on November 26, 2021).

Miller, C., O'Neill, S., Rorig, M., & Alvarado, E. (2019). Air-Quality Challenges of Prescribed Fire in the Complex Terrain and Wildland Urban Interface Surrounding Bend, Oregon. *Atmosphere, 10*(9), 515.

Mitchell, S., Harmon, M., & O'Connell, K. (2009). Forest Fuel Reduction Alters Fire Severity and Long-Term Carbon Storage in Three Pacific Northwest Ecosystems. *Ecological Applications, 19*(3), 643-655.

National Interagency Fire Center. (2020). *Suppression Costs: Federal Firefighting Costs.* Available online: https://www.nifc.gov/fire-information/statistics/suppression-costs (accessed November 18, 2021).

National Public Broadcasting. (2020). *Fast-Moving Wildfire Destroys 80% Of Small Town In Eastern Washington State.* Sept. 8, 2020. Available online: npr.org/2020/09/08/910578980/fast-moving-wildfire-destroys-80-of-small-town-in-eastern-washington-state (accessed November 21, 2021).

National Wildfire Coordinating Group. (2001). *Smoke Management Guide for Prescribed and Wildland Fire*. Available online: https://www.fs.fed.us/pnw/pubs/ottmar-smoke-management-guide.pdf (accessed on November 26, 2021).

Nevada DEP [Division of Environmental Protection]. (2013). Nevada Smoke Management Program 2013. Available online: https://ndep.nv.gov/uploads/air-pollutants-docs/smp-2013-final.pdf (accessed on November 7, 2021).

Nowacki, G., & Abrams, M. (2008). The Demise of Fire and "Mesophication" of Forests in the Eastern United States. *Bioscience, 58*(2), 123-138.

Oak Ridge National Laboratories. (2021). LandScan™: Geographic Information Science & Technology. Available online: https://landscan.ornl.gov/ (accessed November 14, 2021).

Parise, M., & Cannon, S. (2011). Wildfire impacts on the processes that generate debris flows in burned watersheds. *Natural Hazards (Dordrecht), 61*(1), 217-227.

Parks, S., & Abatzoglou, J. (2020). Warmer and Drier Fire Seasons Contribute to Increases in Area Burned at High Severity in Western US Forests From 1985 to 2017. *Geophysical Research Letters, 47*(22), N/a.

Paveglio, T., Kooistra, C., Hall, T., & Pickering, M. (2016). Understanding the Effect of Large Wildfires on Residents' Well-Being: What Factors Influence Wildfire Impact? *Forest Science, 62*(1), 59-69.

Podschwit, H., Larkin, N., Steel, E., Cullen, A., & Alvarado, E. (2018). Multi-Model Forecasts of Very-Large Fire Occurences during the End of the 21st Century. *Climate (Basel), 6*(4), 100.

Podschwit, H., Miller, C., Alvarado, E. (2021). Spatiotemporal Prescribed Fire Patterns in Washington State, USA. *Fire (Basel, Switzerland), 4*(2), 19.

Pollet, J., & Omi, P. (2002). Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire, 11*(1), 1-10.

Price, O., Horsey, B., & Jiang, N. (2016). Local and regional smoke impacts from prescribed fires. *Natural Hazards and Earth System Sciences, 16*(10), 2247-2257.

Prichard, S., Peterson, D., & Jacobson, K. (2010). Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. *Canadian Journal of Forest Research, 40*(8), 1615-1626.

Prichard, S., & Kennedy, M. (2014). Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. *Ecological Applications, 24*(3), 571-590.

Prichard, S., Hessburg, P., Hagmann, R., Povak, N., Dobrowski, S., Hurteau, M., . . . Khatri‐Chhetri, P. (2021). Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications, 31*(8), N/a.

PurpleAir, Inc. (2021). *Sensor Data Download Tool.* Available online: https://www.purpleair.com/sensorlist (accessed November 24, 2021).

Pyne, S. (1982). *Fire in America : A cultural history of wildland and rural fire.* Princeton, N.J.: Princeton University Press.

Quinn-Davidson, L., & Varner, J. (2012). Impediments to prescribed fire across agency, landscape and manager: An example from northern California. *International Journal of Wildland Fire, 21*(3), 210-218.

Ravi, V., Vaughan, J., Wolcott, M., & Lamb, B. (2019). Impacts of prescribed fires and benefits from their reduction for air quality, health, and visibility in the Pacific Northwest of the United States. *Journal of the Air & Waste Management Association* (1995), 69(3), 289-304.

Radeloff, V., Hammer, R., Stewart, S., Fried, J., Holcomb, S., & McKeefry, J. (2005). The Wildland-Urban Interface in the United States. *Ecological Applications, 15*(3), 799-805.

Robinson, M., Zhao, M., Zack, L., Brindley, C., Portz, L., Quarterman, M., . . . Herckes, P. (2011). Characterization of PM2.5 collected during broadcast and slash-pile prescribed burns of predominantly ponderosa pine forests in northern Arizona. *Atmospheric Environment (1994), 45*(12), 2087-2094.

Rockweit, J., Franklin, A., & Carlson, P. (2017). Differential impacts of wildfire on the population dynamics of an old-forest species. *Ecology (Durham), 98*(6), 1574-1582.

Ryan, K., Knapp, E., & Varner, J. (2013). Prescribed fire in North American forests and woodlands: History, current practice, and challenges. *Frontiers in Ecology and the Environment*, *11*(S1), E15-E24.

Schultz, C., McCaffrey, S., & Huber-Stearns, H. (2019). Policy barriers and opportunities for prescribed fire application in the western United States. *International Journal of Wildland Fire, 28*(11), 874.

Schweizer, D., Preisler, H., & Cisneros, R. (2018). Assessing relative differences in smoke exposure from prescribed, managed, and full suppression wildland fire. *Air Quality, Atmosphere and Health, 12*(1), 87-95.
Spearing, L., & Faust, K. (2020). Cascading system impacts of the 2018 Camp Fire in California: The interdependent provision of infrastructure services to displaced populations. *International Journal of Disaster Risk Reduction, 50*, 101822.

Stavros, E., Abatzoglou, J., Larkin, N., McKenzie, D., & Steel, E. (2014). Climate and very large wildland fires in the contiguous western USA. *International Journal of Wildland Fire, 23*(7), 899.

Stein, S., & Rocky Mountain Research Station , issuing body. (2013). *Wildfire, wildlands, and people : Understanding and preparing for wildfire in the wildland-urban interface* (General technical report RMRS ; 299). Fort Collins, CO: United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Stephens, S., McIver, J., Boerner, R., Fettig, C., Fontaine, J., Hartsough, B., . . . Schwilk, D. (2012). The Effects of Forest Fuel-Reduction Treatments in the United States. *BioScience, 62*(6), 549-560.

Stevens‐Rumann, C., Kemp, K., Higuera, P., Harvey, B., Rother, M., Donato, D., . . . Lloret, F. (2018). Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters, 21*(2), 243-252.

Stewart, O., Lewis, Henry T, & Anderson, Kat. (2002). *Forgotten fires: Native Americans and the transient wilderness*. Norman: University of Oklahoma Press.

Thompson, M., Scott, J., Langowski, P., Gilbertson-Day, J., Haas, J., & Bowne, E. (2013). Assessing Watershed-Wildfire Risks on National Forest System Lands in the Rocky Mountain Region of the United States. *Water (Basel), 5*(3), 945-971.

Thompson, M., MacGregor, D., Dunn, C., Calkin, D., & Phipps, J. (2018). Rethinking the Wildland Fire Management System. *Journal of Forestry, 116*(4), 382-390.

Taylor, A. (2004). Identifying Forest Reference Conditions on Early Cut-over Lands, Lake Tahoe Basin, USA. *Ecological Applications*, *14*(6), 1903-1920.

Trauernicht, C., Brook, B., Murphy, B., Williamson, G., & Bowman, D. (2015). Local and global pyrogeographic evidence that indigenous fire management creates pyrodiversity. *Ecology and Evolution, 5*(9), 1908-1918.

Tryner, J., L'Orange, C., Mehaffy, J., Miller-Lionberg, D., Hofstetter, J., Wilson, A., & Volckens, J. (2020). Laboratory evaluation of low-cost PurpleAir PM monitors and in-field correction using co-located portable filter samplers. *Atmospheric Environment (1994), 220*, 117067.

U.S. EPA. [United States Environmental Protection Agency]. (2020). Mortality Risk Valuation. Available online: https://www.epa.gov/environmental-economics/mortality-risk-valuation (accessed on December 13, 2021).

U.S. EPA. [United States Environmental Protection Agency]. (2021a) *Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S.* EPA/600/R-21/197, 2021.

U.S. EPA [United States Environmental Protection Agency]. (2021b) Clean Air Act Text. *Clean Air Act Overview*. Available online: https://www.epa.gov/clean-air-act-overview/clean-air-act-text#toc (accessed on November 18, 2021).

States News Service (2014). USDA Releases State By State Impacts Of Limited Wildfire Suppression In Recent Years List Highlights How Forest Restoration, Fire Preparedness And Other Activities Were Postponed Or Canceled Due To Lack Of Adequate Fire Suppression Budget. *States News Service*, pp. States News Service, 2014-06-09.

Vale, T. (Ed.). (2002). *Fire, native peoples, and the natural landscape.* Island Press.

Washington State Department of Ecology. (2020). *2017 Washington Comprehensive Emissions Inventory Technical Support Document, data, and methods.* https://apps.ecology.wa.gov/publications/SummaryPages/2002012.html (accessed on November 8, 2021).

Washington State Department of Ecology. (2021). *Air Quality Monitoring Network.* https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Air-quality-monitoring-network (accessed November 7, 2021).

Washington State DNR [Washington State Department of Natural Resources]. (1998). *1998 Silvicultural Smoke Management Plan*. Available online: https://www.dnr.wa.gov/publications/rp_burn_smptoc.pdf (accessed November 3, 2021).

Washington State DNR [Washington State Department of Natural Resources]. (2017). *20-Year Forest Health Strategic Plan: Eastern Washington*. Available online: https://www.dnr.wa.gov/publications/rp_forest_health_20_year_strategic_plan.pdf (accessed on October 8, 2021).

Washington State DNR [Washington State Department of Natural Resources]. (2019a). *2019 Silvicultural Smoke Management Plan*. Available online: https://www.dnr.wa.gov/publications/amp_sepa_other_smpupdate_smp.pdf (accessed on October 5, 2021).

Washington State DNR [Washington State Department of Natural Resources]. (2019b). *Washington State Wildland Fire Protection 10-Year Strategic Plan.* Available online: https://www.dnr.wa.gov/publications/rp_wildfire_strategic_plan.pdf (accessed on November 1, 2021).

Washington State DNR [Washington State Department of Natural Resources]. (2020). *Safeguarding Our Lands, Waters, and Communities: DNR's Plan for Climate Resilience.* Available online: https://www.dnr.wa.gov/publications/em_climaterresilienceplan_feb2020.pdf?r5qt4w (accessed on November 21, 2021).

Weaver, H. (1943). Fire as an Ecological and Silvicultural Factor in the Ponderosa Pine Region of the Pacific Slope. *Journal of Forestry*, *41*(1), 7-15.

Weaver, H. (1947) Fire—Nature's Thinning Agent in Ponderosa Pine Stands. *Journal of Forestry, 45*(6), 437-444

Wildland Fire Leadership Council. (2014). *National Action Plan: An Implementation Framework for the National Cohesive Wildland Fire Management Strategy.* Available online: https://www.forestsandrangelands.gov/documents/strategy/strategy/NationalActionPlan_20140423.pdf (accessed on November 8, 2021).

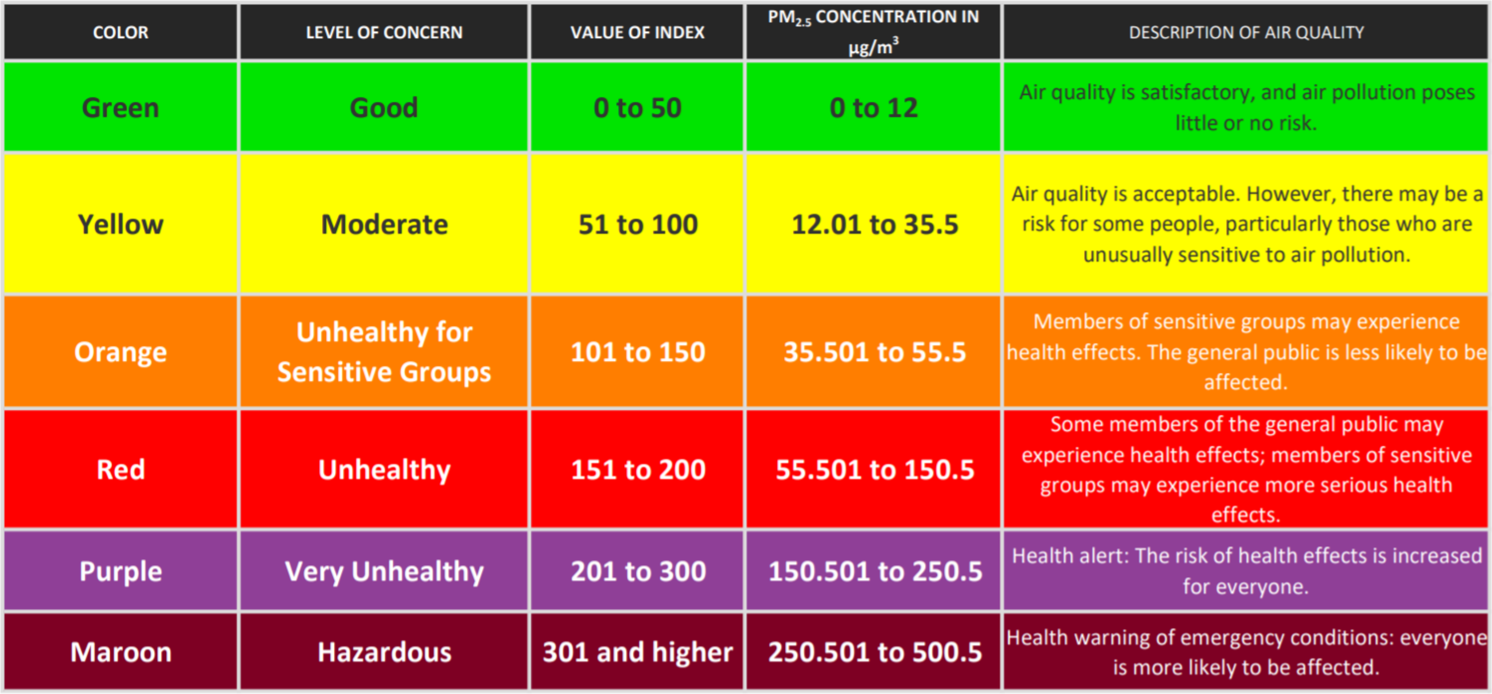
Williams, E. (2021). Reimagining Exceptional Events: Regulating Wildfires Through The Clean Air Act. *Washington Law Review, 96*(2), 765-810.

Williamson, G., Bowman, D., Price, O., Henderson, S., & Johnston, F. (2016). A transdisciplinary approach to understanding the health effects of wildfire and prescribed fire smoke regimes. *Environmental Research Letters, 11*(12), 125009.

Wine, M., Makhnin, O., & Cadol, D. (2018). Nonlinear Long‐Term Large Watershed Hydrologic Response to Wildfire and Climatic Dynamics Locally Increases Water Yields. *Earth's Future, 6*(7), 997-1006.

APPENDIX I

Air Quality Index for $PM_{2.5}$ with associated concentrations in µg/m^3. The NAAQS maximum 24-hour average $PM_{2.5}$ concentration corresponds to 100 on the Air Quality Index.



COLOR	LEVEL OF CONCERN	VALUE OF INDEX	$PM_{2.5}$ CONCENTRATION IN µg/m^3	DESCRIPTION OF AIR QUALITY
Green	Good	0 to 50	0 to 12	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 to 100	12.01 to 35.5	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 to 150	35.501 to 55.5	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 to 200	55.501 to 150.5	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 to 300	150.501 to 250.5	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 and higher	250.501 to 500.5	Health warning of emergency conditions: everyone is more likely to be affected.

APPENDIX II

Dataset 1 (on following page): 24-hour average $PM_{2.5}$ concentrations in μg/m^3 recorded by monitors and sensors within 16 kilometers of a 2019 broadcast burn.

DATASET 1

TARGET _FID	Region	Ignition Date	Burn Permit Number	Burn Latitude	Burn Longitude	Burn Type	Acres burned	Tons burned	Monitor Type	24-hr average $PM_{2.5}$ ug/m^3	Monitor ID	Monitor Longitude	Monitor Latitude
4258	OKANOGAN NF	4/16/2019	40000001379	48.588	-120.346	BROADCAST	4	70	purple_air	0.3	MV Clean Air Ambassador-Little Cougar	-120.2541	48.552
4258	OKANOGAN NF	4/16/2019	40000001379	48.588	-120.346	BROADCAST	4	70	purple_air	0.3	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
4258	OKANOGAN NF	4/16/2019	40000001379	48.588	-120.346	BROADCAST	4	70	purple_air	0.4	AtLast Ranch	-120.3427	48.55374
4258	OKANOGAN NF	4/16/2019	40000001379	48.588	-120.346	BROADCAST	4	70	purple_air	1.4	MV Clean Air Ambassador @ Bush School	-120.4443	48.60941
64003	NE REGION	4/30/2019		48.6044	-118.2061	BROADCAST	4	23	purple_air	3.4	Highland View House	-118.1474	48.71046
2743	NTL PARK SVC	5/1/2019	40000001330	48	-118	BROADCAST	67	0	permanen	3.1	530650002_01	-117.9886	47.8852
4268	OKANOGAN NF	5/1/2019	40000001387	48.573	-120.292	BROADCAST	70	762	purple_air	2.2	AtLast Ranch	-120.3427	48.55374
4268	OKANOGAN NF	5/1/2019	40000001387	48.573	-120.292	BROADCAST	70	762	purple_air	2.7	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
4268	OKANOGAN NF	5/1/2019	40000001387	48.573	-120.292	BROADCAST	70	762	purple_air	8.2	Pit Road	-120.2077	48.48454
4268	OKANOGAN NF	5/1/2019	40000001387	48.573	-120.292	BROADCAST	70	762	permanen	8.9	530470010_01	-120.1906	48.4772
4268	OKANOGAN NF	5/1/2019	40000001387	48.573	-120.292	BROADCAST	70	762	purple_air	15.5	MV Clean Air Ambassador @ Winthrop Library	-120.1902	48.47786
4268	OKANOGAN NF	5/1/2019	40000001387	48.573	-120.292	BROADCAST	70	762	purple_air	43.7	Lazy Cat Ranch	-120.1877	48.52484
64001	NE REGION	5/1/2019		48.6044	-118.2061	BROADCAST	7	44	purple_air	5.1	Highland View House	-118.1474	48.71046
2742	NTL PARK SVC	5/2/2019	40000001330	48	-118	BROADCAST	33	300	permanen	5.3	530650002_01	-117.9886	47.8852
4269	OKANOGAN NF	5/2/2019	40000001387	48.573	-120.292	BROADCAST	70	763	purple_air	1.7	AtLast Ranch	-120.3427	48.55374
4269	OKANOGAN NF	5/2/2019	40000001387	48.573	-120.292	BROADCAST	70	763	permanen	4.9	530470010_01	-120.1906	48.4772
4269	OKANOGAN NF	5/2/2019	40000001387	48.573	-120.292	BROADCAST	70	763	purple_air	6.4	Pit Road	-120.2077	48.48454
4269	OKANOGAN NF	5/2/2019	40000001387	48.573	-120.292	BROADCAST	70	763	purple_air	20.1	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
4269	OKANOGAN NF	5/2/2019	40000001387	48.573	-120.292	BROADCAST	70	763	purple_air	37.2	Lazy Cat Ranch	-120.1877	48.52484
4269	OKANOGAN NF	5/2/2019	40000001387	48.573	-120.292	BROADCAST	70	763	purple_air	58.2	Upper Rendezvous	-120.2422	48.55514
4269	OKANOGAN NF	5/2/2019	40000001387	48.573	-120.292	BROADCAST	70	763	purple_air	130.5	MV Clean Air Ambassador @ Raven Rd	-120.2003	48.54111
63996	NE REGION	5/2/2019		48.6044	-118.2061	BROADCAST	110	698	purple_air	7.6	Highland View House	-118.1474	48.71046
2749	NTL PARK SVC	5/3/2019	40000001388	48.66833	-118.0584	NATURAL	13	80	purple_air	12.8	Highland View House	-118.1474	48.71046
2748	NTL PARK SVC	5/4/2019	40000001388	48.66833	-118.0584	NATURAL	50	350	purple_air	28.7	Highland View House	-118.1474	48.71046
63995	NE REGION	5/4/2019		48.6044	-118.2061	BROADCAST	50	249	purple_air	28.7	Highland View House	-118.1474	48.71046
63999	NE REGION	5/6/2019		48.6044	-118.2061	BROADCAST	50	350	purple_air	2.3	Highland View House	-118.1474	48.71046
63998	NE REGION	5/8/2019		48.6044	-118.2061	BROADCAST	110	775	purple_air	1.0	Highland View House	-118.1474	48.71046
63997	NE REGION	5/10/2019		48.6044	-118.2061	BROADCAST	49	345	purple_air	7.4	Highland View House	-118.1474	48.71046
5520	US FISH AND	5/14/2019	40000001323	48.46976	-117.7198	NATURAL	135	1269	permanent	5.1	530650005_01		
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	permanen	10.1	530470010_01	-120.1906	48.4772
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	permanen	11.0	530470009_01	-120.1211	48.3645
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	12.8	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	14.0	MV Clean Air Ambassador @ Upper Beaver Creek	-120.0445	48.39443
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	14.2	Pit Road	-120.2077	48.48454
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	14.7	MV Clean Air Ambassador @ Balky Hill	-120.1074	48.3778
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	14.9	Frost Road	-120.1801	48.37751
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	15.0	MV Clean Air Ambassador @ Raven Rd	-120.2003	48.54111

63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	15.1	MV Clean Air Ambassador @ Lower Studhorse	-120.1743	48.48526
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	15.2	MV Clean Air Ambassador @ Winthrop Library	-120.1902	48.47786
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	15.5	Lazy Cat Ranch	-120.1877	48.52484
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	17.3	East Pearrygin	-120.1323	48.47289
63974	NE REGION	5/29/2019		48.48932	-120.1117	BROADCAST	24	277	purple_air	26.2	Rolling Rock	-120.2313	48.49313
63962	NE REGION	5/31/2019	NE20180210	48.48932	-120.1117	BROADCAST	22	246	purple_air	19.7	Rolling Rock	-120.2313	48.49313
63962	NE REGION	5/31/2019	NE20180211	48.48932	-120.1117	BROADCAST	22	246	purple_air	20.0	Pit Road	-120.2077	48.48454
63962	NE REGION	5/31/2019	NE20180213	48.48932	-120.1117	BROADCAST	22	246	purple_air	21.3	MV Clean Air Ambassador @ Winthrop Library	-120.1902	48.47786
63962	NE REGION	5/31/2019	NE20180214	48.48932	-120.1117	BROADCAST	22	246	purple_air	23.1	MV Clean Air Ambassador @ Upper Beaver Creek	-120.0445	48.39443
63962	NE REGION	5/31/2019	NE20180215	48.48932	-120.1117	BROADCAST	22	246	purple_air	16.5	MV Clean Air Ambassador @ Raven Rd	-120.2003	48.54111
63962	NE REGION	5/31/2019	NE20180217	48.48932	-120.1117	BROADCAST	22	246	purple_air	29.6	MV Clean Air Ambassador @ Lower Studhorse	-120.1743	48.48526
63962	NE REGION	5/31/2019	NE20180219	48.48932	-120.1117	BROADCAST	22	246	purple_air	14.5	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
63962	NE REGION	5/31/2019	NE20180220	48.48932	-120.1117	BROADCAST	22	246	purple_air	17.8	MV Clean Air Ambassador @ Balky Hill	-120.1074	48.3778
63962	NE REGION	5/31/2019	NE20180224	48.48932	-120.1117	BROADCAST	22	246	purple_air	18.8	Lazy Cat Ranch	-120.1877	48.52484
63962	NE REGION	5/31/2019	NE20180225	48.48932	-120.1117	BROADCAST	22	246	purple_air	14.2	Frost Road	-120.1801	48.37751
63962	NE REGION	5/31/2019	NE20180226	48.48932	-120.1117	BROADCAST	22	246	purple_air	28.1	East Pearrygin	-120.1323	48.47289
63962	NE REGION	5/31/2019	NE20180227	48.48932	-120.1117	BROADCAST	22	246	permanen	12.4	530470010_01	-120.1906	48.4772
63962	NE REGION	5/31/2019	NE20180228	48.48932	-120.1117	BROADCAST	22	246	permanen	12.6	530470009_01	-120.1211	48.3645
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	13.2	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	15.0	Frost Road	-120.1801	48.37751
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	17.4	MV Clean Air Ambassador @ Upper Beaver Creek	-120.0445	48.39443
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	17.5	MV Clean Air Ambassador @ Raven Rd	-120.2003	48.54111
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	21.7	MV Clean Air Ambassador @ Balky Hill	-120.1074	48.3778
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	22.8	MV Clean Air Ambassador @ Winthrop Library	-120.1902	48.47786
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	23.7	Lazy Cat Ranch	-120.1877	48.52484
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	38.6	East Pearrygin	-120.1323	48.47289
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	purple_air	38.6	MV Clean Air Ambassador @ Lower Studhorse	-120.1743	48.48526
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	permanen	12.1	530470009_01	-120.1211	48.3645
63963	NE REGION	6/1/2019	NE20180210	48.48932	-120.1117	BROADCAST	14	154	permanen	12.4	530470010_01	-120.1906	48.4772
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	2.7	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	4.0	Pit Road	-120.2077	48.48454
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	4.2	Frost Road	-120.1801	48.37751
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	permanen	5.9	530470009_01	-120.1211	48.3645
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	6.4	Lazy Cat Ranch	-120.1877	48.52484
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	7.8	MV Clean Air Ambassador @ Upper Beaver Creek (o	-120.0445	48.39443
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	permanen	7.9	530470010_01	-120.1906	48.4772
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	8.9	MV Clean Air Ambassador @ Balky Hill	-120.1074	48.3778
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	13.6	MV Clean Air Ambassador @ Winthrop Library	-120.1902	48.47786
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	24.2	MV Clean Air Ambassador @ Lower Studhorse	-120.1743	48.48526
63972	NE REGION	6/2/2019		48.48932	-120.1117	BROADCAST	29	328	purple_air	26.9	East Pearrygin	-120.1323	48.47289
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	0.2	Frost Road	-120.1801	48.37751
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	0.2	MV Clean Air Ambassador @ Upper Beaver Creek	-120.0445	48.39443
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	0.3	MV Clean Air Ambassador @ Raven Rd	-120.2003	48.54111

63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	0.4	Lazy Cat Ranch	-120.1877	48.52484
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	0.8	MV Clean Air Ambassador @ Balky Hill	-120.1074	48.3778
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	2.0	MV Clean Air Ambassador @ Lower Studhorse	-120.1743	48.48526
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		permanen	2.1	530470009_01	-120.1211	48.3645
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	2.1	MV Clean Air Ambassador @ Winthrop Library	-120.1902	48.47786
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		permanen	2.8	530470010_01	-120.1906	48.4772
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	5.1	East Pearrygin	-120.1323	48.47289
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	0.0	MV Clean Air Ambassador @ Gunn Ranch	-120.2407	48.51911
63971	NE REGION	6/4/2019		48.48932	-120.1117	BROADCAST	44		purple_air	0.0	Pit Road	-120.2077	48.48454
9300	WENATCHEE NF	9/16/2019	40000001401	47.68541	-120.7122	NATURAL	136	2700	permanen	2.2	530070010_01	-120.6647	47.5988