Seeing Environmental Injustice Through Moss-Colored Glasses: Neighborhood Monitoring of Toxic Metal Air Pollution Disparities with Orthotrichum lyellii

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Seeing Environmental Injustice Through Moss-Colored Glasses:

Neighborhood Monitoring of Toxic Metal Air Pollution Disparities with Orthotrichum lyellii

By

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Accepted in Partial Complete of the Requirements of the Degree Master of Arts

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Allison Hayes

December 2023
Seeing Environmental Injustice Through Moss-Colored Glasses:
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A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Arts

by
Allison Hayes
December 2023
Abstract

Toxic air pollution in the United States has been regulated through the Clean Air Act (CAA) since the 1970’s. Yet, a growing body of research suggests that the CAA’s air pollution management system has several blind spots. The CAA’s inability to identify and remedy pollution hot spots across the country. These hot spots are areas where air pollution exists but are often entirely overlooked because of the extreme hyperlocal scale and the current methods for identifying areas of concern outlined in the CAA for the Environmental Protection Agency. Researchers find that these hot spots are more prevalent in minority and low-income communities.

Because of the expense to install and operate traditional stationary air monitors, it is impossible to place a monitoring site in every community. My research explores a potential alternative to the traditional stationary air monitoring system set up in the CAA that may identify pockets of elevated toxic pollution. Using Orthotrichum lyellii as a bioindicator measuring six toxic pollutants, I created maps of potential toxic metal pollution hotspots in the Duwamish River Valley (DRV). This area includes the neighborhoods of Georgetown and South Park separated by the Duwamish River. This industrialized and heavily polluted area in South Seattle was revealed to ultimately contain hot spots of toxic air pollution. This project relied on data collected by community youths. I then applied spatial mapping to illuminate the Duwamish River Valley’s pollution disparities. Through this sort of mapping, it is possible not only to locate potential polluters in an area but to also empower communities to take action and improve the health and safety of the air they breathe.
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In addition to my committee, I would like to thank all the youth volunteers from the Duwamish River Valley Youth Corps, without whom there would be no data upon which to base my analysis. Thank you to the Duwamish River Valley Coalition and the entire community for their willingness to work alongside myself and our research team.

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Introduction

Do you remember experiencing environmental injustice firsthand? Have you seen it with your own eyes? Have you ever found yourself recoiling at the stench of an overfilling landfill in your community, or tasted the bitterness that sticks to your tongue after drinking mistreated water? Have you ever had to second guess your plans for the day because the air in your own neighborhood is dirty enough to smell and you feared for the health of yourself and your loved ones? For some, these are just hypotheticals. Yet, for a very substantial portion of the United States population, these sorts of situations are a very serious reality that must be faced day in and day out. Unfortunately, injustices such as these are often overlooked by those who are not forced to live with them every day – to smell them, to taste them, to feel their constant presence.

Toxic air pollution in the United States has been an issue of concern for years. Air pollution is a problem that affects everyone - after all, we all need to breathe. But how can anyone be certain that the air they are breathing is safe? The United States Environmental Protection Agency (EPA) is largely in charge of ensuring that air quality is protected across the country under the Clean Air Act (see Chapter 1). Though the EPA is charged with ensuring that states are complying with National Ambient Air Quality Standards (NAAQS) and implementing controls for Hazardous Air Pollutants (section 109 of the CAA). Much of the day-to-day work on air quality monitoring is delegated to various organizations within each state, each of which has their own organizations, processes, and methods for monitoring and enforcement.

But despite this fragmentation of responsibilities across organizations, the EPA still maintains a bigger picture understanding of the air pollution problem in the United States, publishing yearly reports into the current state of the air. These yearly reports are intended to give the public an easily accessible snapshot of air pollution trends across the country. At the
time of this thesis’ writing, the most up to date report available is the EPA’s report “Our Nation’s Air: Status and Trends Through 2022”. This report offered some hope for those concerned about air quality, summarizing that “…nationally, criteria air pollutant concentrations have dropped significantly since 1990 improving quality of life for many Americans” (EPA, 2023a). Multiple graphs and figures throughout the interactive report confirm this declaration of decreasing air pollution of all sorts across the nations. The EPA reported improved air quality for decades now, showing an overall declining trend of air pollutants across the country since the early 1900’s (EPA website, 2023b). There is no doubt that the Clean Air Act and resulting air monitoring policies have helped to reduce the amount of pollution that we breathe. However, this short snapshot does not adequately capture the full story. When it comes to air pollution, there is a devil lurking in the details.

Found at the very bottom of the EPA’s interactive Our Nation’s Air report nestled between the headline “Our Nation’s Air Continues to Improve” and links to the Agency’s social media is this fact, “Approximately 85 million Americans lived in counties with air quality concentrations above the level of one or more NAAQS in 2022” (EPA website, 2023b). This is a startling number – of the approximately 333 million Americans alive in 2022, around a quarter live in areas with degraded air quality. But this worrying statistic is made even worse by the fact that flaws in the Clean Air Act may be allowing even more Americans to breathe unhealthy air.
Chapter One: There’s Something in the Duwamish River Valley’s Air
Critical assessments of the Clean Air Act raised concerns about pollution hot spots being masked entirely by the very system designed to indicate where air pollution exists. In a 2018 issue of the UCLA Law Review, an environmental law professor detailed how our federal clean air law was blind to toxic pollution hot spots (Carlson 2018). Localized microclimates can harbor pollution exceeding levels protective of public health obscured by Air Quality Control Regions (AQCRs). Regions are too coarse of a spatial resolution to reveal local pollution clusters. These toxic hotspots also predictably occur around groupings of industrial facilities, congested roads, and minority communities. Likewise, another legal scholar described how an air toxics loophole remained after amendments to the CAA in 1990. “AQCRs swallow hot spots because CAA compliance is based on meeting standards at the regional rather than the local level, and does not distinguish between regional and local air quality data for compliance purposes” (Gonzales 2021, p. 145).

The roots of clean air authority's blindness to hot spots trace to the nation’s first Air Quality Act in 1967. That law ordered states to create Air Quality Control Regions (AQCRs), adopt standards for air pollutants, and develop implementation plans to meet those standards. AQCRs were to be established based on meteorological, topographical, social, and political factors shared by a group of communities. Such regions became the spatial unit for controlling air pollution (Gaulding, 1968). The Seattle-Tacoma region became one of the first 32 urban AQCRs.

Perhaps even more troubling is that many studies have found that these hotspots are most likely to occur in areas with a high proportion of minority and low-income individuals (Gonzalez, 2021; Carlson 2018). A 2015 paper by Ard argues that despite exposure to industrial
toxins decreasing across the nation, the gap between the average air pollution exposure is much higher for Black individuals than their White counterparts even when the Black individuals surveyed were of a higher socioeconomic class (Ard, 2015). This was found to be the case across the country. Such disparities point to a potential for environmental injustice.

Unfortunately, Ard’s (2015) findings indicate that it is not enough to focus solely on reducing pollution as a means of minimizing the risks of environmental harm. This view is further corroborated by a 2019 study using state-level assessment of air quality of the EPA’s Risk-Screening Environmental Indicator (RSEI). Researchers found that while air quality may improve over time, there is still an overall disparity between the risk of exposure (Salazar et al., 2019). In some states, there were even signs of increasing exposure risk and a widening gap of inequality (Salazar et al., 2019). While Washington saw a drop from period 1 to period 2 of toxic air pollution exposure inequality, it increased in period 3. Environmental injustice persists at a state level in terms of pollution, but such inequality exists even at finer scales.

Disparities in South Seattle.

One such instance of environmental injustice is playing out right now in South Seattle’s Duwamish River Valley (DRV). The DRV is an area centered around Seattle’s single river, the Duwamish River. This area in South Seattle has a history of rapid and expansive industrialization and pollution (see Chapter 2). But the DRV is not merely an industrial corridor. According to the EPA, there were around 127,734 individuals living within three miles of the Duwamish River in 2022 (EPA, 2022a). The DRV is not just an industrial hub, but rather is a combination of residential, commercial, and industrial interests. This historically longstanding mix of heavy industry and residential neighborhoods means that the DRV is an area in particular
need of close air quality monitoring to ensure that the byproduct of industrial activities is not having a negative effect on the health and well-being of residents.

Two DRV communities at the center of this study are Georgetown and South Park as displayed in Figure 1. Often represented by the Duwamish River Community Coalition (DRCC), this organization is a key collaborator on this moss study from 2019 – 2023. Funded by EPA assistance agreement (NE-01J78901–0), Duwamish Valley Youth corps teens supervised by community members and researchers collected moss samples in 2021. Expanding a pilot study of 79 locations completed in 2019 (see Derrien et al. 2020 and Jovan et al. 2022a, 2022b), 147 more moss samples expanded the study area. Just over 11 square miles cover an area from the Des Moines Memorial Drive exit on Interstate 99 running North to the West Seattle bridge, westward into the West Duwamish Greenbelt, and east into residential Beacon Hill.

According to the EPA’s Environmental Justice Screening Mapper (https://ejscreen.epa.gov/mapper/), approximately 32,000 people resided in my study area. People of Color make up 60 percent of the area’s population. That is twice the state average. Limited English-speaking households, diesel Particulate Matter (PM in μg/mg3) exposures, and lead paint housing hazards also are all over double the state average (10% to 4%; 0.791 to 0.355; 46% to 23% pre-1960 housing respectively) according to EJ Screen measures. DRV residents also are burdened with 26,000 pounds (lbs.) of industrial air toxics releases compared to a state average of 1,800 lbs. and national average of 4,600 lbs. This puts DRV households in the 99th and 97th percentile for Washington State and nationally for potential air toxic releases exposures.
Figure 1. Study site located in South Seattle indicating locations of the three air monitoring stations, the major point source air polluter facilities (as identified by the EPA) and moss samples from both 2019 and 2021.
Within the South Seattle DRV area there are currently three air monitoring stations used by the Washington State Department of Ecology to determine compliance with the current National Ambient Air Quality Standards set out by the CAA: the Beacon Hill monitor, the Duwamish monitor, and the 10th and Weller monitor (also called the South Park Monitor). The Beacon Hill and the South Park monitors consistently give better readings than the Duwamish monitor, which regularly reports lower air quality. Yet despite the presence of three monitors in the area, residents are concerned that the way data is being collected and interpreted may be allowing for the presence of pollution hot spots to persist within their neighborhoods.

One solution to the concerns of unaddressed pollution hotspots is the use of finer scale monitoring to supplement the already existing air monitoring system. Monitoring projects using this method involves gathering data at a much finer scale than could possibly be collected by the stationary network of monitors set up by the CAA. Such studies instead opt for devices such as smartphones or placing sensors on vehicles to collect real time data at smaller scales (see Yu et al., 2022; Goin et al., 2021). The method of fine scale monitoring for my thesis involves the use of a bioindicator, which is an organism that can be analyzed to gain information about its environment. *Orthotrichum lyelli* is a moss found throughout the south Seattle area and serves as the means of air pollution monitoring in this project.

My study was very similar to one conducted by researchers in Portland, Oregon in 2016 in which moss was used to monitor cadmium pollution as a means of locating potential point polluters (see Donovan et al., 2016 and Gatziolis et al., 2016). For my thesis I plan to expand upon this technique within the Duwamish River Valley area, similar as to the work of Jovan et al. 2022 and Kondo et al. 2023 using the same data as that used in this thesis. While others
pursued more sophisticated methodologies like geographically weighted regression and spatial predictors (Kondo et al.2022), I rely on simpler but equally effective techniques such as spatial clustering tests, geographic hot spots analysis, and kriging. In using these spatial analysis tools and *Orthotrichum lyelli* as a monitor in the Duwamish River Valley, I am seeking to answer the following questions:

1. Can hyper-localized pollution monitoring via moss be an effective tool for identifying patterns of localized air pollution?
2. What are the benefits and drawbacks of this type of monitoring?
3. Are there spatial clusters of toxic air pollution in the Duwamish River Valley area?
4. If so, what do these patterns look like and where are they located?
5. If present, what does the spatial pattern of pollution in Duwamish River Valley show about the potential polluters in the area?
6. How do the observed trends inform understanding about air monitoring sites in the DRV?

Answering these questions involves a combination of spatial analysis techniques that ultimately result in the creation of interpolation maps highlighting potential point pollution being overlooked in the Duwamish River Valley area.
Chapter Two: Policing Pollution
Air pollution has been a concern in all parts of the globe for centuries. Many scholars point to the rise of the Roman Empire in which smoke was a public nuisance as one of the first instances of air pollution litigation (Chen et al., 2007; Stern, 1982). Some of the earliest noted air pollution disputes in the United States date all the way back to the country’s founding, at a time when such disagreements were settled by private litigation between the involved parties rather than governmental legislation (Stern, 1982). Commonly, air pollution issues were handled as being a common or private nuisance. It was not until around 1881 that legislation was first introduced specifically to declare emissions of public smoke as a public nuisance, thus allowing citizens to hold one another more formally accountable for air pollution (Stern, 1982). Much of this early pollution was concentrated in urban areas, and began to worsen as cities grew (Mosley, 2014). As industrialization continued to rapidly march forward and coal grew increasingly used in development, the need for more and much stronger, uniform regulation in air pollution became increasingly clear to both citizens and government alike. In the 1960’s, phenomena like acid rain started to cause public concern in the United States, compounding with already existing concerns about the effect of increased urbanization and development (Stern, 1982).

These concerns would eventually become a topic of conversation at the United Nations Conference on the Human Environment in 1972, further amplifying the growing need for sound and standardized air pollution policy (Mosley, 2014). This conference was not only significant for “bringing world leaders together for the first time to talk about the state of the earth”, but also for highlighting the extreme difficulties of regulating air pollution, many of which still plague policymakers today (Mosely, 2014, p. 158). One example of such problems is that fact that air pollution in one area could affect another hundreds of miles away. This makes air pollution incredibly tricky to contain and regulate. The United States’ first attempt at a truly
comprehensive air quality and pollution legislation would be enacted a few years prior to the UN meeting in 1970. This legislation is known as the Clean Air Act.

The Clean Air Act (CAA) was originally signed on December 31st, 1970, by then President Richard Nixon as a part of a plan focused on “growing the American economy stronger while protecting the health of the country’s citizens” (EPA, 2010). The CAA would later be amended in 1977 and again in 1990 to address emerging issues such as the unique challenges that metropolitan areas faced in the process of meeting attainment goals and the persistent concern of acid rain (EPA, 2022b). But despite the amendments made throughout the years, the main thrust of the CAA has remained the same: an increased responsibility for the federal government in terms of the creation of guidelines and enforcement of air policy at a national level. The CAA remains the definitive guiding policy for air pollution regulation at a federal level in the United States to this day.

Perhaps the most critical component of the CAA was and remains its authorization for the U.S. Environmental Protection Agency (EPA) to create a set of air quality standards that would apply to all states in the nation. These standards would come to be known as National Ambient Air Quality Standards (NAAQS). The CAA set up NAAQS to target six key common pollutants: particulate matter (PM$_{2.5}$ and PM$_{10}$), lead, carbon monoxide, nitrogen dioxide, and sulfur dioxide. These six pollutants were chosen to be “criteria” air pollutants because of the threat they may potentially pose to human and environmental health (EPA, 2023c). The CAA dictates that the NAAQS are to be reassessed every five years to ensure that they are up to date with the most current available science (EPA, 2023c). Importantly, NAAQS are meant to be based solely off concern for public health, which means that when revising standards, the EPA is not meant to consider the cost of changing the NAAQS – public health and the current scientific consensus
are supposed to guide any changes made to the standards (Harvard Law, 2023). This all means that in theory, the CAA should provide equal standards and protection across the entirety of the United States. But this expectation has been proving to be far from reality.

**Criticism of the Clean Air Act**

The CAA has come under an increasing amount of scrutiny as pollution has continued to pile on in many places over the years since the law’s enactment. In 2021, California Attorney General Xavier Becerra, alongside sixteen other attorney generals, filed a lawsuit against the Trump administration for their failure to tighten the NAAQS regarding ozone standards, given the new science indicating that the current standards are inadequate to reach the goal of human health and environmental protection (Bonta, 2021).

As mentioned, the CAA is meant to respond to new scientific understanding by reevaluating of the current standards. And yet no proposed changes had been made despite new research calling for an adjustment of existing CAA standards, according to Becerra and others (Bonta, 2021). The lawsuit also alleged that the EPA “conducted a flawed and unlawfully biased review of the current NAAQS” that blatantly ignored emerging science (Bonta, 2021).

Some action has been taken in the time since to remedy this situation made by President Trump’s predecessor, but ultimately this discussion of NAAQS, their current state, and their potential revision misses the bigger picture of the problems at play in air pollution monitoring.

The CAA is far from an ironclad piece of policy, and indeed has many flaws that make ensuring equitable protections for all a difficult task to manage. Attorney General Becerra’s complaints are valid, but the main thrust of the lawsuit rests on the assumption that the national air monitoring system is even able to adequately monitor for the six pollutants outlined in the NAAQS using standardized pollution caps. But air pollution is very difficult to simplify down to
one perfect number of ‘acceptable’ hazard. These pollutants all vary across time and space according to numerous factors including climate, geophysical and economic conditions, population density and location of emitters. All of this makes the monitoring and regulation of pollution a tricky endeavor, even under the guidance of the CAA (Colmer et al., 2020).

Still, it seems on the surface that tightening NAAQS is the surest method to improve air quality under the current CAA regulation. It may not be perfect, but at least it will tighten regulations for everyone. But the assumption underlying this solution that stricter NAAQS will meaningfully remediate the air pollution problem misses the fact that at its very core the CAA is ill-equipped to meaningfully and fairly regulate air quality in the United States. Many of the complaints against the CAA fall in line with the aforementioned grievances aired by Attorney General Becerra: NAAQS need to be updated more frequently and with more mindfulness to current scientific understanding of the effects of key pollutants on public health. But there is an even deeper problem at play in our nation’s air monitoring system, and that is the very design of the system itself.

As such, this thesis will largely forgo critiquing the current state of the NAAQS rulemaking specifically and instead falls in line with the growing body of criticism asserting that the entire design of the national air monitoring system by its very nature necessitates unequal monitoring and pollution response. The system in its current state is too limited by its very design, and therefore attempts to simply tighten NAAQS do not adequately address the growing air pollution problem in the nation. The CAA, in its current form, is simply unable to ensure that air pollution is being accurately monitored and remediated in every area that needs it. This is not to say CAA is not a useless piece of policy. It has had significant impact both on bringing air pollution to the forefront of governmental concern and on the declining air pollution across the
nation. But the CAA works in broad strokes and hot spots of air pollution require a finer scale approach.

Currently, the monitoring scheme set up by the CAA involves the use of numerous stationary air monitoring sites across the nation, some of which may have multiple monitors operating at once to collect data on various substances of concern. These monitors are not exclusively overseen by the EPA but rather the EPA under the authority of the CAA passes along some portion of the responsibility of monitoring to various state entities. EPA guidelines dictate that each state is responsible for developing and selecting their own ambient air monitoring network that aligns with the requirements of the CAA (EPA, 2023d). This means that the decision of how and where to place monitors is largely up to each individual state and its relevant governing bodies, provided they follow baseline requirements outlined in the CAA.

Figure 2 is a graph created for the EPA’s 2017 Air Quality Monitoring Network report which illustrates how the various responsibilities of ambient air quality monitoring are broken down by EPA and state/local responsibility (EPA, 2017a). There is overlap in some areas such as trends analysis, but overall, the day-to-day of tasks such as emergency control and real time reporting through the air quality index system (AQI) falls mainly on the shoulders of the state government. This means that despite the CAA
standards being national, there is a considerable room for variation across states in terms of governmental involvement, management, and ultimately, air quality.

As of 2022 the EPA estimates there are approximately 4,000 monitoring stations across the country being used to assess ambient air quality, most of which are under the jurisdiction of varying state and regional environmental agencies (EPA, 2022a). The exact number of monitors within each state varies. In their 2015 Washington State Ambient Air Monitoring Network Assessment, the Department of Ecology reported having 110 monitors operating across 68 stations in the state (WA Department of Ecology, 2015). By 2020, this number had increased to 75 monitoring stations (WA Department of Ecology, 2020). In some cases, monitors have been removed and later reinstated, such as monitors in Burbank and Tulalip that were removed only to be later reinstalled (WA Department of Ecology, 2020). In the 2020 report, Ecology states that they are “wary of recommending any sites for removal that may need monitoring in the future”, indicating that there are no plans of further immediate monitor removal due to the removal and reinstatement process often being “much more costly and labor-intensive that continued operations” (WA Department of Ecology, 2020, p.2).

Ecology’s Ambient Air Monitoring Network Plan reports that there were 72 monitoring sites operating across Washington as of July 1st, 2022 (Schulte, 2022). These monitors are not all operated by one entity. Instead, responsibility for Washington’s air is divided up among several agencies: Northwest Clean Air Agency, Puget Sound Clean Air Agency, Olympic Region Clean Air Agency, Southwest Clean Air Agency, Yakima Regional Clean Air Agency, Benton Clean Air Agency, and the Spokane Regional Clean Air Agency. These agencies work alongside the Washington State Department of Ecology to ensure that the state is meeting national standards.
The decentralized air quality protection of Washington state exemplifies the EPA policy of subdividing air pollution responsibility across a large range of air authorities.

This is not to say that the method of delegating responsibility is a downside of the CAA. The segmentation of responsibility can be helpful in creating a system of checks-and-balance as well as ensuring that one entity is not overwhelmed by the sheer amount of work necessary to keep air quality in check. But designating so much of the decision making and monitoring up to each individual state is not without its drawbacks.

In their 2007 article on the administrative flaws in federal regulations of Hazardous Air Pollutants (HAPs). Also known as air toxics, Victor Flatt pointed out some of the most striking issues with the enforcement of HAPs. Flatt claimed that in many ways the “legislative mechanisms of the [Clean Air] Act are unworkable precisely because of the problems they leave in enforcement and administration” (Flatt, 2007, p. 111). Throughout their report, Flatt stressed that this varying level of enforcement across different states and localities is one of the largest flaws in the CAA’s regulation of HAPs. To illustrate this, Flatt compared air quality enforcement across different states to point out how much they vary.

These differing levels of enforcement mean that depending on the state in which you live, you may have tighter enforcement of CAA regulations as well as being subject to additional air pollution regulations on top of what is required by the CAA. Your state may not have additional air quality safeguards and in some areas may not even be attaining CAA goals. All of this is despite the fact all states being under the same blanket federal air monitoring policies. Some states, such as California, have numerous additional policies on top of federal guidelines as well as strict reporting measures beyond that required by the CAA to improve air quality, whereas
other states are lagging behind (Flatt, 2007). Thus, it is logical to assume that this system of varying levels of policy and enforcement could easily become a breeding ground for inequality.

Flatt goes on further to point out the difficulties that come into play when trying to set up an administrative system that is prepared to handle the identification and easing of pollution hot spots. These hot spots are of major concern because they are areas of the risk of high pollution exposure that often go undetected. Pollution is quite literally slipping under our radar in many places across the country. According to Flatt, these situations can be difficult because the same sort of technological requirements in place to monitor major sources are “successful in cutting overall emissions, it is not necessarily the best way to address localized pollution hot spots. At the same time, establishing standard technology requirements at a level that will address hot spots means that there may be "too much" regulation in many places” (Flatt, 2007. p. 165). Flatt warns that creating a situation with too much red tape (even when administered with relative efficiency) can end up causing more harm than good. Thus, in many areas the broad strokes of a command-and-control strategy of the Clean Air Act can be “too blunt to address every area's unique problem and pollution sources” (Flatt, 2007, p. 166). Hot spot pollution requires a more nuanced approach that is tailored more specifically to the area in which it is present.

Flatt is not the only one to critique the current air monitoring system and is in fact only one in a long line pointing out the shortcomings of the current air monitoring system set up by the Clean Air Act. For example, a 2020 report by the Government Accountability Office (GAO) on the current air quality monitoring system found it to be extremely “inflexible and outdated” (GAO, 2020, p. 58). The GAO report further outlines the shortcomings of the EPA’s handling of air pollution, stating that the “EPA is responsible for ensuring that the monitoring system
provides a consistent level of service across the country; however, we found inconsistencies across EPA regions in how EPA has addressed its management challenges” (GAO, 2020, p. 56).

The complaints go further. A 2020 Reuter’s report showed that in some cases air monitors across the U.S. routinely miss toxic releases from industrial fires and day-to-day pollution disparities (McLaughlin et al., 2020). This report claims that often, air monitors are not getting the same reading as auditing monitors placed directly beside them (McLaughlin et al., 2020). Throughout their article, the author’s mention numerous refinery explosions occurring and there being little to no record of such events being picked up by EPA air monitors despite thousands of individuals being hospitalized over the resulting air pollution. This is often the case with monitors that are set up to only operate on some days, such as when a Philadelphia refinery exploded in 2019. In that instance, the monitor was not operating on the day of the explosion. The surrounding monitors also failed to detect any change in air quality, being located too far away or upwind and therefore not able to pick up in the change caused by the incident (McLaughlin et al., 2020).

These findings echo the concerns of Flatt and many others who believe that there are gaps in the CAA that are being overlooked. Ultimately, the flaws in the CAA such as the current program guidance and system of existing monitors resulted in the GAO concluding that the current system of air monitoring is in desperate need of a “modernization plan” (GAO, 2020, p. 58).

One solution to this problem may seem to be as simple as providing more monitors as this would allow the EPA and state entities to collect more data and create a more accurate picture of pollution across the United States. This would in turn allow for tightening of regulation and a better understanding of where pollution actually exists across the country. But the methods for
the CAA’s air pollution monitoring system require expensive and stationary monitoring equipment (Snyder et al., 2013; Donovan et al., 2016), meaning that acquiring new monitors and setting up new stations can be a serious financial strain on the government. In many cases, the placement of these monitors can be tricky, given the amount of land encompassed in the States. Ensuring that every neighborhood has their own monitoring site is simply not feasible under the CAA’s current model, so decisions must be made about where and who will receive monitors.

As noted, EPA guidelines dictate that each state is responsible for developing and selecting their own ambient air monitoring network that aligns with the requirements of the CAA (EPA, 2022b). This means that the decision of where to place monitors is largely up to each individual state and its relevant governing bodies, provided they follow baseline requirements outlined in the CAA. The EPA’s frequently asked air monitoring question site explains that, in general, “states choose to site monitors in areas with higher concentrations and/or higher population since the minimum monitoring requirements are based on population size. Therefore, many small towns and communities don’t have monitors” (EPA, 2022b). This statement highlights one of the blind spots of the EPA and the CCA’s guidance: areas that are not densely populated or are not already expected to have high levels of pollution are oftentimes being passed over entirely for monitoring.

Though the EPA emphasizes that the decision making on monitor location varies across states, it remains common practice for less populated areas to be lacking monitoring sites (EPA, 2022b). This appears on the surface to make practical sense: areas that are more heavily populated tend to have more pollution, and by placing monitors here it is serving more people than in a rural area. But though this method seems sound, it ultimately results in large parts of the
population lacking adequate air pollution monitoring. The current system also ignores any potential alternatives to provide service to less populated areas.

But basing monitor locations solely on population can have serious consequences for those who do not live in densely populated areas. Such was the case in Superior, Wisconsin in 2018 when an oil refinery exploded, causing 36 workers to be injured and over 2,500 residents to be evacuated out of fear of air quality hazard (KARE11, 2018). Despite Superior and the neighboring Duluth, Minnesota being covered in thick black smoke, the city of 27,000 was not considered large enough to require the EPA place any air quality monitors nearby (McLaughlin, 2020).

**Concerns for environmental injustice**

It cannot be over-emphasized how much the *where* of these monitors matters. Since the 1960’s civil rights movement, environmental justice has been pushing to the forefront of environmental consciousness. During this time, there was an increasing concern over the trend of racial minority groups and those of lower socioeconomic status being forced to deal with a greater number of environmental hazards than their White and wealthier counterparts (Bullard, 1983; United Church of Christ, 1987; Pulido et al., 1996). Mohai et al.’s 2009 analysis demonstrates that even today, environmental hazards tend to manifest in minority populated communities because of longstanding and historical systems of oppression that have resulted in economic disparities and segregated communities (Mohai et al., 2009).

The Environmental Protection Agency defines environmental justice (EJ) as “the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies” (EPA, 2021a). Environmental injustice therefore occurs in
instances of unfair treatment and little or meaningless involvement. The definition of environmental justice become relevant to the handling of the CAA in 1994 when President Bill Clinton signed Executive Order 12989 (Clinton, 1994). This Order demands that all government agencies “identify and address the disproportionately high and adverse human health or environmental effects of their actions on minority and low-income populations, to the greatest extent practicable and permitted by law” (EPA, 2023f). But despite this strong declaration by the federal government that programs such as air quality monitoring should be subject to safeguards against environmental injustice, this has simply proven not to be in the reality of air pollution in the United States.

In Jbaily et al.’s 2020 study, serious disparities in air pollution exposure were found across the United States. Researchers found that the populations with higher-than-average Black, Asian, and Latino populations were exposed to higher levels of particulate matter compared to populations with higher-than-average White and Native populations (Jbaily et al., 2020). Other studies of air pollution exposure across the United States further demonstrate the disparity, such as the finding by Zuo et al. that racial minorities as well as low-income individuals and those with less than 12 years of education were at higher risk of exposure to benzene air pollution than their counterparts (Zuo et al., 2014). Miranda et al.’s 2011 analysis of air pollution exposure across the U.S. found that non-Hispanic Blacks were consistently overrepresented in those communities with the poorest air quality (Miranda et al., 2011). These are just a few of the many examples of environmental injustice as it relates to air pollution distribution and serve to demonstrate that there is a massive blind spot in the CAA that unfortunately cannot be fixed by the existing mechanisms of the system itself.
Because the current system of air quality monitoring depends entirely on air monitoring sites across EPA regions, it is impossible to get a clear picture of pollution purely from this data. This means that it is possible many communities are not receiving the attention and protection they need. Even more worrying is the compounding environmental injustices that may be at play in many of these neighborhoods. The prohibitive costs and labor required to monitor every community in every corner of the country means that instead the EPA and the public must rely solely on the coarse scale data collected by existing monitoring sites. But there are other potential solutions that involve the use of finer scale, local air pollution monitoring to better understand where hotspots of pollution occur across the country.

**EPA Air Sensor Loan Programs**

It should be noted that the EPA does offer a potential alternative for those in areas without monitors, or who feel that they are not being given an adequate picture of pollution within their neighborhood. This opportunity comes in the form of the EPA’s Air Sensor Loan Programs. These programs are offered across all the EPA’s ten regions and were created “independently and through collaborations with libraries, tribes, museums, and others to enable the public to learn about air quality in their communities” (EPA, 2023g). These programs vary wildly from one another, as each is set with its own individual goals, equipment, and structure. They also vary in eligibility.

![Figure 3. Illustration of the EPA's air sensor loan program guidance.](image-url)
(EPA, 2023g). Figure 3 shows the EPA’s general guidance for setting up air sensor loan projects in five simple steps. This study follows a similar structure to those programs but diverges in a few ways.

Because these programs already exist, it is important to assess whether this is a potential avenue for solving the issues of air quality monitoring. On one hand, these programs are a great alternative for the current air quality monitoring as they allow individuals the chance to get into the field and collect data on their own for purposes such as monitoring wildfire smoke or observing the difference in air quality when close to major highways. For example, the Los Angeles public library offers portable sensors that can be checked out to gather air quality data around the city. Washington state has a similar program, though administered by one of the agencies already responsible for air quality monitoring in the state, the Puget Sound Clean Air Agency.

But do these programs truly fill the gap present our air quality monitoring scheme? Put simply, no. These programs are intended for outreach and educational purposes (EPA, 2023g) which, while admirable, is not enough to fully address the fundamental flaws of the CAA system. Further, there are limitations on what sensors are available to what regions as well as a great deal of variation in the loan application process, the length of loans, trainings available as well as many other factors.

For example, the Los Angeles Public Library loan program in EPA Region 9 provides hands on in person training with library staff, whereas other regions provide no additional training except a link to the EPA’s online Air Sensor Toolbox. Some Region’s programs require that the participants provide Wi-Fi or microSD whereas others do not. The application process for these loans varies considerably from program to program. But most importantly is that some Regions
have multiple programs, whereas others only have programs that are slated to begin soon, such as Region 6 which lists only that the program launch date has still not been determined or Region 2 which currently hosts no active programs, but as two slated to begin sometime in 2023 (EPA, 2023g).

Despite the aforementioned shortcomings, these programs should not be written off entirely as they still have value for those able to participate. Loan programs such as this provide an alternative to traditional monitoring even with the limited scope of less technologically advanced monitors than those used by the CAA. Education and outreach are important aspects of creating a better air pollution future, but these alone are not enough to offer a meaningful solution to the pollution problem.

Because of the nature of independent loan offerings, the problem of unequal access to air monitoring that plagues the CAA persists even here. Programs such as these offer potentially powerful alternatives able to point out the flaws within the CAA framework by identifying hotspots that may otherwise go undetected by the EPA’s CAA monitoring scheme. Still, we cannot yet celebrate the existence of such programs when their current design leaves so much room for inequality. These loan sensor programs may be a part of a larger solution, but as they presently stand, they act as little more than a band-aid to the CAA regulatory wound. That is why the methods in this thesis rely heavily on low-cost, widely available bioindicators that can be collected by anyone in nearly any place.
Chapter Three: Air Pollution Data – Long Overdue for a Neighborhood View
In their 2018 review of the Clean Air Act, Ann E. Carlson identified one of the blind spots in the CAA as a lack of awareness as to the variation in pollution across small microclimates. Here, a microclimate refers to the set of atmospheric conditions within an area that differ from the conditions of the larger surrounding area. Importantly, these microclimates can contain dangerous levels of pollution that are not detected by the widescale monitoring system set up by the CAA. This lack of detection can occur in areas where monitoring stations are present (Carlson, 2018). Communities of color as well as low-income communities tend to be the ones living in highly polluted microclimates, once again underlining the potential for environmental injustice to occur within the existing framework of the CAA (Carlson, 2018). This means that the large-scale monitoring scheme set up by the CAA can leave many small communities behind by focusing on large scale data that can mask the nuances of pollution present in microclimates. Many of these communities then will not receive the remediation required to reach CAA compliance because no sufficient data is being collected at a proper scale to provide evidence of the problem.

The EPA breaks down the question of scale for air quality monitoring into six distinct subcategories: micro, middle, neighborhood, urban, regional, and national/global. Definitions of these subcategories can be seen in Table 1, adapted from the EPA’s Quality Assurance Handbook (EPA, 2017a). In these terms, clean air agencies work at an urban or regional scale. But while this can be an efficient model in terms of data collection and analysis, it is not necessarily appropriate for identifying hotspots within microclimates. Instead, a neighborhood or middle view is needed.

For example, in a 1993 article, Koening et al. found that there can be considerable differences in air pollution over even small areas. In their study of North Seattle, it was found
that “some areas along creek drainages gave [sic] quite high concentrations of fine particulate matter on cold, clear nights, whereas nearby areas on adjacent ridges have two to three times lower concentrations” (Koeing et al., 1993, p. 27).

<table>
<thead>
<tr>
<th>Measurement Scale</th>
<th>EPA Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>Concentrations in air volumes associated with area dimensions ranging from several meters up to about 100 meters.</td>
</tr>
<tr>
<td>Middle</td>
<td>Concentrations typical of areas up to several city blocks in size with dimensions ranging from about 100 meters to 0.5 kilometer.</td>
</tr>
<tr>
<td>Neighborhood</td>
<td>Concentrations within some extended area of the city that has relatively uniform land use with dimensions in the 0.5 to 4.0 kilometers range.</td>
</tr>
<tr>
<td>Urban</td>
<td>Overall, citywide conditions with dimensions on the order of 4 to 50 kilometers. This scale would usually require more than one site for definition.</td>
</tr>
<tr>
<td>Regional</td>
<td>Usually, a rural area of reasonably homogeneous geography and extends from tens to hundreds of kilometers.</td>
</tr>
<tr>
<td>National/Global</td>
<td>Concentrations characterizing the nation and the globe as a whole.</td>
</tr>
</tbody>
</table>

*Table 1. Measurement scale definitions from the EPA’s Quality Assurance Handbook (2017).*

**Urban average representation?**

Though conducted to the north of the DRV, this study exemplifies some of the complications of air pollution monitoring. Capturing the nuance of microclimates and pollution hot spots is no simple task. In the case of Seattle, these differences across space and time were further tested in by Wu et al.’s 2011 study assessing cancer risk using selecting hazards air pollutants (HAPs). In this case, six different locations were monitored across Seattle, including Beacon Hill. Ultimately, the study concluded that “operating multiple air toxics monitoring sites over a significant period of time (e.g. more than one year) with proper monitoring frequency would be a necessary step in understanding population's exposure to HAPs” (Wu et al., 2011, p. 16). The researchers found that there was simply too much variation and nuance for any monitor to fully capture, particularly when monitors are only recording occasionally.
In the case of Seattle, a siting workshop was held in May of 2000 to determine what areas were most in need of and most suitable for a stationary air monitor (Goswami et al., 2002). The goal of this workshop was to “optimize scarce resources” by quantifying the spatial characteristics that make a site representative of the average population exposure in Seattle (Goswami et al., 2002, p. 325). But the problem with such an approach is that hot spots are not average. While it is practical to aim for representing the average exposure of a Seattle resident, such a monitoring scheme misses out on the critical details that can have serious impacts on health and safety.

Goswami identifies the Beacon Hill monitor as an urban scale monitor, meaning that it is used for “overall, citywide conditions with dimensions on the order of 4 to 50 kilometers” (EPA, 2017a). The problem with this is that, as mentioned, this is looking at the issue at too coarse a scale. Looking at the Duwamish River Valley (or any other community) from such a coarse scale perspective means that hotspots of pollution can easily be missed as these require much closer examination to be identified. Attempting to represent average exposure is one way to quantify air pollution, but this approach misses out on some of the key features of a pollution landscape. It is also worth noting that Goswami’s research concluded that the most suitable area for monitoring the average Seattle residents exposure to toxic air pollution was in the Maple Leaf neighborhood, not Beacon Hill. While a monitor was placed in Maple Leaf in 2001 based on this finding, it is no longer operating (PSCAA, 2010).

The benefit of finer scale data is further evidenced in the EPA’s Technical Guidance for Assessing Environmental Justice in Regulatory Analysis gives an overview of the importance of scale in terms of data analysis (Figure 4). According to the EPA’s Guidance document, finer-scale data such as that at a middle of neighborhood level tends to lead to a higher level of
confidence in the resulting analysis (EPA, 2016). Finer-scale data also tends to take more time and labor to obtain, but ultimately offers more flexibility and confidence. This is contrasted by coarse-scale data with which “the ability to assess change in risk across populations and other conclusions is more limited” (EPA, 2016). For data such as air quality, fine-scale data at a local level is critical to identify hot-spots that could be missed by larger scale data. Coarse-scale data such as a regional or urban scale approach is still incredibly useful and should continue to be used to gain an overall understanding of general trends within air pollution, but the growing awareness of pollution hot-spots in numerous communities across the country demands a finer scale approach.

Figure 4. An adapted version of the EPA’s data quality and spatial resolution in the context of air regulation chart.
Clark et al.’s 2022 analysis of air pollution disparity in the United States also supports the need for finer scale analysis. In this study, researchers examined the extent to which data aggregation impacted the estimate of exposure disparities. It was found that estimates based on state and county scale vastly underestimated risk exposure estimates from tract and block group data (Clark et al., 2022). This idea of the importance of considering scale is corroborated by studies such as Bowen et al.’s analysis of the spatial distribution of toxic industrial pollution in the Ohio area. Bowen’s analysis found that while county level examination of urban counties found a high correlation between race and toxicity, this was not present at a census-tract level. This variance in pollution levels depending on the scope of analysis emphasizes the importance of spatial scale in studies of environmental hazards (Bowen et al., 1995).

Scale and spatial data

To further understand the importance of scale, it is necessary to understand the nature of spatial data. Spatial data is unique in many ways, and thus has its own set of unique problems. One of these well-known issues is called the modifiable areal unit problem (MAUP), which is “the problem that occurs with aggregation of spatial data by modifying the size, shape (or zone), and/or orientation of spatial categories/polygons in geographical data. Such alteration of spatial categories can theoretically regroup observations...
among polygons into infinitely new and different arrangements and thereby recast the data” (Buzzelli, 2020, p. 169). An example of the way MAUP can lead to skewed understandings of data can be seen in Figure 5. MAUP is a problem when assessing air quality because the scale at which pollution is assessed is incredibly important when the time comes to use said data to inform decision making. It is very easy for the nuance of potential pollution hot spots to become lost or even go undetected due to improper data aggregation. Collecting and utilizing finer scale data is one way to alleviate this problem; however, it is impossible to gather the necessary data at the needed scale using the current air monitoring system. This issue of data aggregation in decision making has had a serious impact on the state of air quality monitoring, with areas such as the Duwamish River Valley being overlooked due to poor methodology (see chapter 3).

Figure 6 is a graph created by the EPA showing the current trend of air pollution emissions across the whole United States. By all accounts, this graph stands as evidence of the
roaring success of current air pollution policy; yet, when considering the scale of the data in light of the MAUP it becomes obvious that this image does not tell a full story. While air pollutant emissions may be decreasing overall across the county, this does not mean that the problem is improving everywhere. According to the American Lung Association’s (ALA) 2023 “State of the Air” report, there was a decrease of around 17.6 million fewer individuals breathing unhealthy air compared to the previous year’s figures (ALA, 2023).

But much like the EPA’s report, the ALA’s State of the Air should not be overgeneralized. The report summary goes on to highlight that despite this overall downward trend, “nearly 36% of Americans—119.6 million people—still live in places with failing grades for unhealthy levels of ozone or particle pollution” (ALA, 2023). But what is perhaps most alarming is the finding that “the number of people living in counties with failing grades for daily spikes in deadly particle pollution was 63.7 million, the most ever reported under the current national standard” (ALA, 2023). Obviously, looking at the population as a whole is useful at times and can provide an overall picture of trends, but it should never be assumed that trends for the larger populations apply at smaller scales. This tendency for decrease in overall trends while disparity remains is further corroborated in works such as Salazar et al.’s 2019 analysis of pollution inequality. To understand what is happening in these smaller population samples a new method of data collection is needed that focuses on investigating trends at the smaller, neighborhood level.

The current monitoring scheme laid out by the Clean Air Act is simply not sufficient to capture all the details of pollution. There is an incredible nuance to the methods of air monitoring that finer scale monitoring can capture. More attention is now being put on instances of hotspot pollution being overlooked because of the current methods used by the EPA (see
Donvan et al., 2016; Derrien et al., 2020; Abel et al., 2008; Jovan et al., 2022), but it is worth noting that in that the opposite is also occurring. There have been instances in which air monitors are overreporting the severity of air pollution in certain areas, such as in California when the entire district of West and downtown Los Angles was labeled as an “extreme nonattainment zone for ozone” under NAAQS regulation because of the large number of violations being reported on San Bernardino monitors within the same region (Carlson, 2008, p. 1104). Both the under and over reporting of air pollution are problems that can be solved by shifting more attention to microclimate pollution through hyperlocal monitoring (though it is noteworthy that Carlson strongly emphasizes the underreporting is much more common than the overreporting). Having access to such fine-scale data could allow for decision makers to more accurately assess which areas are receiving more attention and resources than necessary and inform how to redirect and redistribute to help ease the burden of air pollution in communities suffering the most.

Such a widescale analysis of air pollution as is currently being conducted fails to adequately address issues of pollution hot spots at local levels. Importantly, many of these hotspots are located within marginalized communities. Carlson summarizes the issue that as “our current system of air pollution regulation-while enormously successful- may actually mask pollution hotspots, leaving those who are exposed to them unaware of their health risks and in some cases misleading regulators about their existence” (Carlson, 2018, p. 1042).

In a similar vein to Carlson, Magdalena Filipiuk Gonzalez further emphasizes this critical issue at the heart of the CAA monitoring as being that “[pollution] hot spots tend to form in predominantly non-white, impoverished communities, where socioeconomic disadvantages compound the negative effects of environmental harms by exacerbating health problems and limiting economic growth” (Gonzalez, 2021, p. 138). Gonzalez also compares the air quality
monitoring in various states, pointing out that even states with very intense regulation such as California still have pockets of pollution within these already marginalized communities that are not being addressed.

A more rigorous and modern set of air pollution monitoring policies is desperately needed to challenge the gaps present within the CAA. Hyperlocal monitoring projects are beginning to grow more common across the globe. For example, in Yu et al.’s 2022 study researchers demonstrated how taxis could be used to gather PM$_{2.5}$ data across China. Yu’s team found that in urban areas where traditional monitors were present there was an overrepresentation of pollutant exposure compared to what was found using the finer scale taxi method. The opposite was true of rural areas, which have significantly fewer monitors but higher potential for disproportionate exposure to air pollutants than is being captured by existing regulatory measures (Yu et al., 2022).

In 2021, Goin et al. investigated the way that exposure to air pollutants like NO$_2$ and black carbon can increase chances of preeclampsia in pregnant woman using a car-based monitoring method (Goin et al., 2021). Goin emphasizes that “using hyper localized measures of air pollution is especially important in a city like Oakland, which has densely populated neighborhoods near multiple industrial and traffic sources of pollution with hills and other complex terrains that traditional methods cannot effectively capture” (Goin et al., 2021, p. 14711). Every corner of the U.S. has its own ‘Oaklands’ – cities and communities where the complex nature of the terrain, zoning, and pollution profile make it nearly impossible for traditional monitoring systems capture a full picture of the landscape and associated risks. The Duwamish River Valley is one such ‘Oakland’, though through finer scale neighborhood
analysis it may be possible to identify such complexities that become washed away in urban scale approaches to monitoring.
Chapter Four: The Duwamish River Valley: A Brief History of Pollution Past and Present
For the purposes of this thesis, this brief history section will not present an entire story of the DRV, but rather aims to highlight the history of industry and pollution in the area. That said, I would like to take this space to acknowledge that the Duwamish River Valley lays within the ancestral lands of the Duwamish Tribe. Though the history of the Duwamish Tribe will not be discussed here, their stewardship both past and present has preserved and shaped the face of the Duwamish River Valley since time immemorial.

**Shaping the face of the Valley**

The Duwamish River Valley is a sight of interest in terms of environmental justice because of its longstanding history of industrialization, pollution, and community action against encroaching environmental harm. The Duwamish is the only river in Seattle, flowing from South Park to Georgetown into Elliott Bay. A 1950 report assessing the state of the river for potential industry expansion identified the Duwamish Valley as having “most of the essentials for industrial sites”, among which are a level topography and readily available energy sources (Carlson, 1950, p. 150). These and numerous other industry-attracting features were critical in the development and expansion of the Valley and continue to make the DRV an attractive site for businesses.

![South Seattle - Duwamish River Valley](image)

*Figure 7. A map of the South Seattle Duwamish River Valley with an insert map highlighting the study site location in context of Seattle’s geography.*
Beer production is one of the oldest industries to have taken a foothold in the DRV during the twentieth century and it was this growing industry that ultimately helped define the Valley as a working-class community during the early 1900’s. As the beer industry blossomed, the Valley came to be heavily populated by migrant communities from East Europe, Asia, Germany, and Italy (Cummings, 2020). This history of immigration is vital to the identity of the DRV, as the area remains a working-class neighborhood largely populated by lower income and minority individuals (EPA 2022a; Department of Neighborhoods, 2019). Given this longstanding demographic makeup of the area coupled with heavy push for industrialization, the problems facing the DRV may reflect deeper rooted issues of environmental injustice.

In 1917, the Boeing Airplane Company purchased the Heath Shipyard in South Seattle and converted it into a factory (Cummings, 2020). This first factory marks the beginning of a long relationship between the Boeing Company and the Duwamish River Valley that has spanned on for decades. The impact of Boeing entering the DRV cannot be overstated, as the company continued to expand over the years, becoming one of the largest employers in the area. Because of the demands of World War II, Boeing soon sought to expand further in the DRV. As a result, Plant 2 was created in 1936 in Georgetown. By the end of World War II, the plant had expanded out to being nearly 1.7 million square feet (Boeing, n.d.). Between just the years of August 1940 and February 1944 the Boeing Aircraft Company produced around 7,000 B-17s as part of the answer to then President Roosevelt’s 1940 call for at least 50,000 planes to be built a year to support the ongoing war effort (Boeing, n.d.). This massive order served to further solidify Boeing in the area as an industrial giant and a major employer. It also produced a substantial amount of hazardous waste.
Boeing and other industries now had a serious foothold in the Valley, which also meant that their production waste had also found a new home. It is estimated that by the mid-1960’s Boeing had “already shipped twenty-four million gallons of industrial waste to [the] two disposal sites, and its annual volume of waste was on the rise” (Cummings, 2020, p. 102). These dumping sites were almost exclusively located in the DRV. This dumping by Boeing and other industries did serious harm to the DRV, particularly the river itself (Cummings, 2020). Plant 2 was later destroyed as part of environmental cleanup and remediation in 2011, but the impact of the Boeing Aircraft Company’s presence on the Duwamish River Valley remains to this day.

It is important to note as well that World War II also had a major impact on the demographics of the Valley. Previous forced displacement of the Native people had already had a serious impact on the area’s population, and the forced internment of all individuals of Japanese descent because of Executive Order 9066 would have a lasting impact on the demographics of the DRV. Prior to the war, South Park had a population around 12% Japanese, which shrunk drastically to 1% (Cummings, 2020). In their place, according to Cummings (2020), came Latino and Black families. These communities remain a massive part of the DRV’s identity. The Duwamish River Community Coalition estimates that as of 2022, around 42% of the DRV population are people of color, and that around 21% are below the poverty line (Duwamish River Community Coalition, 2022). Because of this high percentage of non-white and poor residents, there is reason for particular concern over potential environmental injustice occurring in the DRV.

In the 1960’s, residents began to raise concern about increasing levels of pollution in the area. It was around this time that a group of South Park housewives decided to protest a waste dump that was causing serious harm to the everyday lives and health of the city’s residents.
(Cummings, 2020). Concerns such as these would continue into the 1970’s and 1980’s as more and more improper waste dumping by numerous industries was being uncovered throughout the DRV area. Improper industrial waste disposal was becoming a serious problem as industries were running out of room not only for their factories but also their waste, including harmful chemical by-products that posed a risk to the health and safety of residents and the environment (Cummings, 2020). The protest by South Park housewives demonstrates that not only is the history of the DRV one that is inextricably tied to industrial pollution, but also community action and environmental consciousness.

In the late 1950’s and into the 1960’s the government found themselves facing extreme pressure from businesses in the DRV who wished to see Seattle’s thriving industrial corridor expanded (Cummings, 2020). Industrial interests were placing pressure on the government to rezone much of the area surrounding the Duwamish River, stripping it of its residential classification and allowing for the further expansion of industry in the area. Residents of South Park fought hard against this proposed change, insisting that they be allowed to keep their homes and neighborhood over the interests of industry. In February of 1968, the city of Seattle agreed to end the plan to transition the whole of South Park into an industrial zone due in no small part to the pressure on decision makers by DRV residents (Cummings, 2020). But despite the win this represented for the residents of South Park, their troubles would only continue for years to come as pollution in the Valley continued to accumulate and worsen.

**Lower Duwamish Waterway Superfund Site**

As time went on, the DRV continued to experience higher and higher levels of pollution, and eventually the rising concern over the health and safety of the Duwamish River led to a
response from the EPA. In 2001, the Duwamish River was declared a Superfund site (notably, the EPA refers to the area as the Lower Duwamish Waterway, not the Duwamish River Valley). EPA designated Superfund sites are those areas such as landfills and manufacturing facilities that are highly contaminated with unsafe materials. These sites are given special attention and funding by the EPA for cleanup and remediation. The EPA currently estimates that remedial action on the Lower Duwamish Waterway will begin between September and November of 2025 (EPA, 2023e).

The river being named a Superfund site is no doubt a win for the DRV and its residents, but unfortunately this project still fails to address many of the pollution problems in the Valley.

This Superfund site cleanup of the Lower Duwamish Waterway is a joint effort between the EPA and the Washington State Department of Ecology. According to the EPA’s website “the EPA is responsible for administering the cleanup of sediments in the Waterway, and the Department of Ecology is responsible for controlling sources of pollution to the Waterway” (EPA, 2023d). The descriptions of both responsibilities relate explicitly to the waterway itself, and do not make any mention of other pollutants that plague the area surrounding the river. The Superfund Site refers directly to the Duwamish River and does not address any of the concerns about the air pollution that is a direct consequence of the very same decades of pollution that caused the waterway to become contaminated. Steps are being taken to reduce the harm of
pollution overall in the DRV, but this does not eliminate the need to assess and remediate the harm of air pollution. Cleaning the water does not make the problem of dirty air any less dangerous.

Unfortunately, even given the intervention of the EPA on the issue of the water itself, much of the plight of the Duwamish River Valley residents remains the same as it has for nearly a century. It is estimated that as of 2009, the Duwamish Valley still constitutes around eighty percent of Seattle’s industrial land base (Duwamish River Community Coalition, 2010). The demographics of the area also remain largely similar to their historical makeup, with rates of poverty and percentage of non-white residents remaining higher with the South Park area than in the surrounding Seattle city (Duwamish River Community Coalition, 2010; Department of Neighborhoods, 2019). Community groups such as the Duwamish River Community Coalition (DRCC; previously Duwamish River Cleanup Coalition) are working to improve conditions of both the water and the surrounding neighborhoods, but industrial pollution has not stopped in the South Seattle area, nor has it become a problem concentrated only in the river.

One of the biggest concerns presently remains that of air pollution despite the EPA seemingly overlooking the issue in their handling of the cleanup. In the Department of Neighborhood’s 2019 South Park Snapshot report residents of the area rated one of their top concerns as “air pollution and health outcomes” in addition to ongoing concern about the water and encroaching gentrification (Department of Neighborhoods, 2019; Duwamish River Community Coalition, 2010).

**State of the air in the Duwamish River Valley**

Air pollution continues to be a persistent issue in the Duwamish River Valley that is aggravated further by frequent industrial accidents. Industrial fires pose a serious threat to the
safety and quality of the air in the Valley. During the time of this thesis work, the Duwamish River Valley experienced one of these accidental industrial fires. On September 12, 2022, during a Zoom videoconference with partners from the Duwamish River Community Coalition, collaborators on this project who were in the South Park neighborhood alerted the research team that a fire just ignited at a nearby scrap yard as the meeting was commencing. They shared video recordings of a smoke plume rising above the area and sweeping across the Valley. A similar fire occurred in May of 2017 and mobilized an emergency response from the Environmental Protection Agency (EPA 2017b). A year later, another fire at the same scrap yard made local news (Kiro7 News, 2018; King5 News 2018; Pacheco-Flores 2018). These fires pose a serious risk to residents of the Valley because while it is possible to contain fires, there is no way to stop smoke laced with dangerous chemicals from spreading in the air and entering the lungs of DRV residents.

This brings the story of the Valley up to the present day, and the question of how air is currently being monitored in the DRV. Currently within the South Seattle area are three air monitoring stations used by the Washington State Department of Ecology to determine compliance with the current National Ambient Air Quality Standards set out by the CAA: the Beacon Hill monitor, the Duwamish monitor, and the South Park monitor. Unfortunately, despite the presence of three monitors in the area the DRV is still not receiving an adequate picture of pollution.

Figure 9 shows a map created by the Washington State Department of Ecology in July of 2023 that highlights those areas which the Department considers to be “of concern” for air quality. Areas at higher risk are featured in red and orange, though areas marked with a yellow symbol are still considered to be a larger concern than other unmarked areas across Washington.
Notably, the South Seattle/Duwamish River Valley area is not highlighted as an area of concern. But this does not mean that the DRV’s air is as safe and clean as it should be. Rather, this map reveals a deeper problem in the Washington Department of Ecology’s methodology for assessing the current state of air pollution. These methods harm not only the residents of the Duwamish River Valley, but other areas within Washington that may be flying under the Department’s radar.

As mentioned, there are three stationary air monitoring sites in the DRV. But one key factor at play is the location of the monitors within the Valley. Location is critical in air pollution monitoring, as the location of said monitoring site can have a serious impact on the quality and consistency of readings. In the case of South Seattle, two of the three monitors (the Duwamish and the South Park stations) are located within the Valley itself whereas the Beacon Hill monitoring station is, as the name implies, sitting atop a hill. Further, the Beacon Hill monitor is
located inside a golf course. The location of these monitors and their relation to surrounding major point source air polluters is shown in Figure 10.

![Google maps screenshot of the Duwamish River Valley showing monitor and point polluter locations.](image)

Figure 10. Google maps screenshot of the Duwamish River Valley showing monitor and point polluter locations.

It is clear to see from this image that the conditions surrounding the Beacon Hill monitor are vastly different than those of the Duwamish and South Park stations. As stated, the Beacon Hill monitor is at a higher elevation and is further away from the other two monitors which are stationed in the Valley proper, positioned much closer to the industrial corridor. But these differing conditions are not necessarily a problem when the data is assessed individually. The information being collected by the Beacon Hill air monitoring station is as valuable as any other air quality monitor’s data; however, the way that this data is being used by the Washington State Department of Ecology is seriously skewing the perception of pollution in the Valley.

Tackling the trouble of air quality in the DRV must begin with a critical assessment of the current methods being used to monitor and summarize air pollution. In this case, to decide whether the DRV is an area of concern the WA Department of Ecology uses the data from all
three monitors to decide. But the flaw in their methods comes in the choice to combine and average together the readings of these three stations as opposed to assessing the data from each monitor individually. The Department of Ecology is choosing to look at the problem of pollution in the DRV on too coarse a scale. Looking at the DRV through the lens of an urban scale has resulted in the Department missing out on a considerable amount of nuance present with the DRV microclimate.

![Box-whisker plot](image_url)

*Figure 11. Box-whisker plot of air pollution from five separate monitors comparing the concentration of heavy metals to various regulatory standards.*

This all is to say that because of the choice of scale that the Department is using to make their assessments, the consistently cleaner Beacon Hill data may be skewing the overall picture of pollution within the Valley as a whole. This difference in air quality between the three monitors is shown in Figure 11 which displays the difference in the daily PM$_{2.5}$ average between all three monitors, as well as monitors in Seattle and Houston, Texas across 2019. Following Washington State standards, both South Park and the Duwamish monitor exceed the recommended PM$_{2.5}$ concentration by 52 and 46 days, respectively. The Beacon Hill monitor did not have a single day over the state limit.
This problem worsens still with tighter regulations, such as when compared to the recommendation of EPA’s Clean Air Scientific Advisory Committee (CASAC). Following this standard, South Park and the Duwamish monitor exceed the limit 153 and 137 days of the year, whereas the Beacon Hill monitor recorded only 9 days exceeding the recommended limit. This is the data that is being averaged by the WA Department of Ecology to determine the level of air pollution concern facing the Duwamish River Valley.

Clearly, scale is a problem in the case of the DRV’s air monitoring. The method of averaging forfeits nuance for the sake of simplicity and efficiency, but in doing so creates cracks that communities can easily fall through. It is incredibly important to emphasize that getting the scale wrong in this case is not just a matter of methodological mishap. This lack of attention paid to potential pollution pockets has real-time impacts on the life, safety and well-being of the thousands of people who call the DRV home.

The history of industrial pollution and the Duwamish River Valley is long standing and deeply intertwined, but this history is also not yet at a close. Residents of the DRV continue to fight to this day for recognition and remediation of environmental hazards in their air and water. It is because of all of this that the Duwamish River Valley has been selected as the study site for this thesis. The residents should not have to fear for their safety for the simple act of breathing. Though this thesis represents only one small part of easing the burden on the DRV, it is an important step forward to the recognition of a problem existing in the area with the goal of providing a potential line of evidence to make change happen and create a healthier and safer Duwamish River Valley.
Chapter Five: A Community Moss Model
Community science model

For the purposes of this thesis, the term “community science” is used in place of the more popular “citizen science”. Though citizen science is the term most often utilized in the current literature, this language may exclude and be harmful to those members of a community who lack full legal citizenship. The value of these individuals’ contributions to the scientific process and their communities should not be diminished in any way due to their citizenship status. For this reason, the terms “community member” and “community science” will be used in place of the less inclusive yet more widespread “citizen” and “citizen science”.

Community science is the process by which researchers “engage the public in making observations and collecting and recording data” and has been growing more popular as a research method in recent years (Washington Sea Grant, as cited by Snyder et al., 2013). These community members most often serve as volunteer field researchers and do so across a plethora of disciplines (Cohn, 2008). For a researcher, community science is appealing for a few reasons, the most obvious of which being the availability of the public to serve as “a free source of labor, skills, computational power and even finance” (Silvertown, 2009, p. 467). However, the use of community science can require tradeoffs that should not be overlooked.

In many cases, community scientists are used in place of professional researchers and graduate students because it is simply too costly to hire enough trained researchers, particularly for studies that are large in scope (Cohn, 2008). While this is not the case in every instance of community science use, it is crucial to remain mindful that researchers are not exploiting the labor of volunteer scientists or taking critical opportunities away from trained researchers by means of proper compensation to the volunteers and limited, mindful use of volunteer labor.

Community science is incredibly important in terms of environmental justice work. The very field of environmental justice is grounded in community advocacy, and the need to bring
together a wide range of stakeholders to address issues of systemic injustice (Williamson, 2022). One key criticism of the current model of public participation is that often, community members are not fully integrated into the decision-making process. This is why many justice and policy scholars critique the current public hearing model, decrying that it is not sufficiently allowing for the public to meaningfully be involved in the policy process (Hunt, 2019). Community science offers an alternative opportunity for meaningful public involvement that is not limited to the traditional public hearing model.

Community science does not strictly benefit scientists and researchers, but also offers enrichment for the volunteers as well. Community science allows for anyone to participate in the scientific process as opposed to the elite few that have historically dominated scientific research (Silvertown, 2009). This means that those who have been traditionally left out of scientific endeavors have a chance to explore their scientific curiosity and participate with mainstream science in a meaningful way. Community science is not just a powerful tool for gathering data, but also can be a form of justice by breaking down the barriers to scientific involvement.

Further, community science can serve as a form of public outreach, and by extent a means of accountability particularly for projects that are funded through taxpayer money (Silvertown, 2009). Community science allows researchers to demonstrate the value of their work to the taxpayer and the communities in which they are operating. Silvertown concludes their comprehensive overview of the current state of community science by arguing that “undoubtedly the best way for the public to understand and appreciate science is to participate in it” (Silvertown, 2009, p. 470).

Engaging community members with research is far easier now than ever, with access to software and materials that can be more readily available to the public through the Internet.
These resources can be used to engage an exceptional wide audience who may not typically be able to participate with traditional academic research, such as the case in Southern Africa where nonliterate volunteers were able to use a tracker device to observe animal movements and behavior within their own localities (Lundmark, 2003). Allowing a group such as nonliterate individuals that have been traditionally left out of scientific research to engage and contribute in a meaningful way not only broadens the diversity within the scientific community, but also empowers community members to engage with their own surroundings. This same principle can be applied to youth volunteers who collected moss samples used in this thesis.

Previous work in community-based monitoring by Derrien et al. (2020) indicates that youth volunteers are not only capable of collecting quality samples, but also that engagement with projects such as this one may increase their overall understanding and awareness of the issue at hand.

**Biomonitoring**

For this thesis, a biomonitor was used to monitor air pollution. Biomonitors are “biological processes, species, or communities and are used to assess the quality of the environment and how it changes over time” (Holt & Miller, 2011, p.1). Moss and lichen are commonly used as one such bioindicator that can offer a means of monitoring that is much cheaper and more efficient than traditional air monitoring methods (Donovan et al. 2016; Gatziolis et al., 2016).

There are a few characteristics that make moss a powerful tool for monitoring pollution, the first of which being their ability to accumulate pollution over time (Gatziolis et al., 2016). The waxy coating on mosses and lichens also aids in their bioindication abilities as they are able to absorb water over their entire surface. This is critical because moss and lichen do not have the
typical root systems that other plants use in order to absorb nutrients from the soil – instead, moss takes up all their nutrients from the atmosphere. Another feature of moss is its high cation exchange capacity which essentially helps the plant’s cells capture nutrients during rain as well as trap pollutants such as heavy metals (Gatziolis et al., 2016; Aboal et al., 2011). Because all of this in addition to the low cost of using moss as a bioindicator, moss studies as a method have the potential to be exceptionally effective in studies with an emphasis on community involvement as a tool to solve environmental injustices.

Numerous studies have been conducted previously utilizing the moss study technique to monitor air pollution across varying geographies and time scales (Gjengedal & Steinnes, 1990; Nickel et al., 2014; Steinnes, 1995; Gerdol et al., 2002; Rühling & Tyler, 1986). A review conducted by Bargagli (2016) of moss and lichen as bioindicators for mercury pollution found that while the uses of the data collected via moss studies may be limited in some regards, such data can be extremely valuable in finding the hot spots of pollutants of interest. Though Bargagli’s review is focused on mercury pollution, this largescale review of moss and lichens as a bioindicator supports the use of such organisms as effective indicators for other types of pollution monitoring. Additionally, Bargagli’s synthesis of previous moss/lichen studies offers a framework of key points necessary for a moss study to be successful: “these programs require the choice of an appropriate biomonitor species, standardized sampling and analytical procedures, adequate quality and quantity of data, suitable statistical elaboration, and presentation of the results” (Bargagli, 2016, p. 224). This framework was used as a basic guideline for this thesis.

Following Bargali’s framework’s call for a suitable species, the moss *Orthotrichum lyellii* serves as the biomonitor species for this study. *O. lyellii* has been tested as a biomonitor in the
past and proven to be effective at locating hot spots of heavy metal pollution. In a study conducted by Donovan et al. (2016), a similar method as this thesis’ was used to test the effectiveness of moss studies in detecting the presence of cadmium, a heavy metal. In this case, *O. lyellii* was successful in monitoring the levels of cadmium within the study areas, allowing for the identification of hot and cold spots of cadmium pollution (Donovan et al., 2016). This data was later used to pressure the polluters to cease operations, after which cadmium levels in the study area dropped (Donovan et al., 2016). The results from Donovan et al. (2016) serve as a strong example not only of the effectiveness of moss (specifically, *O. lyellii*) as a bioindicator but also the potential of moss studies as a whole. Notably, other studies have also been conducted using *O. lyellii*, such as Field’s (2020) survey of heavy metal presence in the Pacific Northwest. Both studies conform to Bargagli’s (2016) framework for successful moss studies.

*O. lyellii* will serve as the bioindicator for this study. But collecting moss alone is not enough to fulfill Bargali’s framework. The methods for standardized sampling can be found outlined in Chapter 5. But to make the data collected from this moss and therefore the study meaningful, there must be suitable statistical elaboration (Bargagli, 2016). To do so, this thesis will differ from previous studies such as Donovan et al., 2016 and Kondo et al. 2020. The methods for this thesis will rely on spatial analysis, particularly examining the metal concentrations in mosses for spatial autocorrelation in order to ultimately create a prediction surface of six key metal pollutants.

**Spatial autocorrelation and interpolation**

The most popular methods for establishing spatial autocorrelation are called exploratory spatial data analysis (ESDA) and can be broken down into two large subdivisions: global and local spatial autocorrelation. Global here is used to indicate that the overall trend of data is being
identified in order to identify areas of clustering at various locations across space. Local spatial autocorrelation focuses on telling where clustering occurs. This allows for those locations where patterns diverge from the overall trend of the data to be identified. One method often used for testing spatial autocorrelation is the Moran’s I test, which can be conducted on both a global and a local scale. Moran’s I is a measure that is often used to test for “the presence of spatial dependence” (Li et al., 2007, p. 1). This tool gives a picture of whether observed pattern is clustered, random or dispersed. Moran’s I is used across a number of disciplines including pollution monitoring, particularly in studies within China (see Zhang et al., 2008; Yao et al., 2020; Liu & Lin, 2019). This measure is a critical building block in determining where spatial patterns of pollution exist within the South Seattle area.

Another common method of spatial analysis for identifying areas of interest is hot spot analysis, which evaluates statistically significant clusters by calculating z-scores based on the Getis-Ord Gi* statistic (Ord & Getis, 1995; Getis & Ord, 2010; Kim & Choi, 2017). Numerous other studies have employed similar methods for assessing hot spots of all varieties, from crime to pollution to disease (see Lersch et al., 2014; Maroko et al., 2020; McClintock, 2012). This method does not necessarily focus specific locations of high concentrations, but rather is useful in identifying clusters of concentrated pollution or areas with a lack thereof (Kim & Choi, 2017). While Moran’s I and the Gi* statistic are similar to one another, Moran’s I gives a sense of whether there is similarity between features nearby one another, whereas the Gi* statistic tells whether or not there are concentrations of high and low values. These two statistics are linked to one another but are not necessarily the same despite often finding similar areas of significance (Ord & Getis, 1995). In the case of this study, the use of Gi* will allow for identification of both high and low concentrations areas to search for patterns in either, as the absence of contaminants
in certain areas may be just as crucial as areas of high concentration in understanding the spatial patterns and potential causes of pollution.

Spatial interpolation is the process of using data points with known values to make estimates for other unknown values. This process can be incredibly valuable in creating pollution maps from point data, such as the case with moss samples from the South Seattle area (see Jovan et al., 2022). Kriging is a specific kind of spatial interpolation that can be used to create a prediction surface map. This method has been used to create maps of air pollution, such as in Tyagi and Singh 2013 study using kriging to create a map of air pollution present in Agra, India. Other studies have also used this method to create maps of pollution, both air and sediment (see Liu 2015; Khosh Eghbal, 2014). In the case of South Seattle, kriging will be a powerful tool in understanding patterns of pollution across the entirety of the study area to help more easily identify potential sources of pollution as well as patterns of pollutants that change over distance from probable polluters.
Chapter Six: Methods
Sample collection and preparation

Data for this project were collected in both 2019 and 2021 and the sampling methods for each collection and laboratory analysis are outlined in Jovan et al. (2022).

In short, samples of the moss Orthotrichum lyellii were collected across a 250x250-m grid within the South Seattle neighborhoods of Georgetown and South Park. Members of the Duwamish Valley Youth Corps (DVYC), in addition to several adult volunteers, collected moss samples in both years from trees closest to the centroid of each grid cell (Jovan et al., 2022). Youth from the DVYC were instructed on the best procedures for collecting moss samples, including where on a tree is best for sampling and how to harvest the upper 2/3rds of the moss stems for analysis. The accuracy of youth sampling was verified by the expert adult samplers, who re-sampled in nineteen of the grid cells. A total of 79 moss samples were collected in 2019 and another 147 samples were collected in 2021.

After collection, the Orthotrichum lyellii samples were sent to the U.S. Forest Service’s Grand Rapids, MN laboratory. Samples were prepared for analysis by being dried for 24 hours at 40 °C, after which they were ground into a homogenous powder for analysis. Following this:

“a 0.500-g subsample of each moss sample was processed using a modified microwave-assisted digestion with 10 mL concentrated HNO₃ + 2 mL 30% H₂O₂ + 2 mL concentrated HCl. An overnight pre-digestion of the samples with added reagents was done at room temperature. Following the microwave-assisted digestion cycle, digests were transferred by rinsing with deionized water to 50 mL volumetric flasks, diluted to volume with deionized water, and filtered through 0.45-um membrane filters into plastic storage bottles prior to analysis. Concentrations of 25 elements in total were measured by inductively coupled plasma optical emission spectrophotometry” (Jovan et al., 2022: p. 5).

This procedure was applied to both the 2019 and 2021 moss samples which produced two datasets. These data were then shared by the U.S. Forest Service laboratory with the Western
Washington University research team and associated partners. All recorded data are published to Dryad for public use and can be found here: (https://doi.org/10.5061/dryad.tqjq2bw1p).

Data analysis

Several steps were required to complete my analysis of the moss sample data. Figure 12 presents a flowchart illustrating the steps taken throughout my analytical process. The first step in my analysis was to determine if the 2019 and 2021 moss samples could be combined into a single dataset. To test the feasibility of combining the two datasets, t-tests were run to assess if the two datasets represented the same population – the same airshed, in this case. Upon finding no significant differences between the two datasets and no statistical anomalies, the two years of data were combined into one dataset. This combined dataset (2019 and 2021) contains a grand total of 226 moss samples and was used in the rest of the analysis.

![Flowchart of the steps of my analytical methods.](image)

The next step in my analysis included creating a set of point pattern maps based on metal concentrations found in each of the moss samples. In doing so, it becomes possible to visualize
the spatial distribution of toxic metal pollution present in the Georgetown and South Park neighborhoods within the Duwamish River Valley. Six priority metals are of particular interest in my research, including: arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), and nickel (Ni). Therefore, the following maps depicted in Figures 14-18 show information for only these six metals. Each map uses the natural breaks classification schema (or Jenks method) with 5 class breaks.

**Global Moran’s I**

A fundamental assumption of statistical analysis is independence of observations. In this case, the levels of metal concentrations should be independent and unrelated across the moss samples. However, when the independence assumption is not met, the data are said to exhibit spatial autocorrelation. Spatial autocorrelation is a technical term for the fact that spatial data from near locations are more likely to be similar than data from distant locations. As such, spatial autocorrelation relates the value of the variable of interest in a given location with values of the same variable in surrounding locations. This leads to my next step, testing the moss samples for the presence of spatial autocorrelation in metal concentrations.

The test most often used to evaluate spatial autocorrelation is Global Moran’s I (Getis, 2007; Li et al., 2007). Importantly, the Global Moran’s I tests only whether spatial autocorrelation is present but does not give any indication of *where* that spatial autocorrelation exists. Global Moran’s I simply evaluates if a variable shows a random, dispersed, or clustered pattern. Importantly, Global Moran’s I is an inferential statistic, which is to say that “results of the analysis are always interpreted within the context of its null hypothesis” (ESRI, 2022b). In this case, $H_0$ is that the pollution within the DRV is randomly distributed, meaning that there is
no spatial autocorrelation. Global Moran’s I determines whether this is the case, or if the spatial
distribution pattern differs from the $H_0$ assumption of random distribution.

To perform a Global Moran’s I test, the moss dataset was loaded into ArcGIS Pro and the
Incremental Spatial Autocorrelation tool was used to determine an appropriate distance band for
each metal. Using a beginning distance of 300-meters, setting the distance increment to 50-
meters, and selecting 20 distance bands, this tool created line graphs displaying the distance or
distances where spatial autocorrelation was present for each metal. These peak distance values
were selected to represent where the “spatial processes promoting clustering are most
pronounced” (ESRI, 2022a). Though some metals showed multiple peaks, ultimately the smallest
distance where a peak was visible was selected for the distance band due to the generally small
size of the study area.

Global Moran’s I was calculated to test for spatial autocorrelation in each metal using the
Univariate Moran’s I tool in GeoDa software. In order to conduct the tests, it was necessary to
create a spatial weights matrix for each metal (Dubin, 2009; Getis, 2009). A spatial weights
matrix is essentially a relevant neighborhood set for each observation in the moss dataset. Only
moss samples that belong to the neighborhood set of a given sample point exert influence. As
such, creating a spatial weights matrix is a way to impose restrictions on the nature of
interactions between the moss samples. The spatial weights matrix for each metal was created
with the Weights Manager tool using the previously determined distance band for each metal.
Inverse distance was applied so that while all moss samples in the neighborhood set of a given
sample point exert influence, the magnitude of influence diminishes with distance. Once the
spatial weights matrices were created, the Global Moran’s I was run for each metal. The results
of each test were randomized by 999 permutations in order to assess the significance of the tests. Summary statistics from the six Global Moran’s I tests are presented in Table 2.

**Local Moran’s I**

Global Moran’s I is a global measurement and only shows if spatial autocorrelation is present across the study area. On the other hand, Local Moran’s I (Anselin, 1995) and Getis-Ord Gi* (Getis & Ord, 1992; Ord & Getis, 1995) are local measures highlighting where spatial autocorrelation is present. While these tests are similar, they offer different information, and both are required to gain a full understanding of spatial trends occurring across South Seattle. Local Moran’s I makes it possible to visualize clusters and outliers, as well as find where the value at an observed sample point coincides with what is expected based on values at surrounding points. Local Moran’s I, therefore, gives measures of both positive and negative spatial autocorrelation. Getis-Ord Gi* identifies locations where either high or low values cluster together, or hot and cold spots of metal concentrations. Unlike with Local Moran’s I, the Gi* statistic only captures positive spatial autocorrelation. Positive values imply clustering of high values while negative values indicate grouping of low values. It is not possible to discern spatial outliers with Gi*.

Using the same spatial weights matrices from the global tests, a Local Moran’s I was calculated for each metal with the Univariate Local Moran’s I tool in GeoDa software. This tool produces a Local Indicators of Spatial Association (LISA) cluster map for each of the six metals. The core idea of Local Moran’s I is to identify cases in which the value of an observation and the average of its surroundings is either more similar or dissimilar than we would expect from pure chance (Anselin, 1995). Positive forms of local spatial autocorrelation are of two types: high-high (H-H) clusters represent areas where values at the site and its surroundings are larger than average; and low-low (L-L) clusters where low values are surrounded by other low values. Negative forms of local spatial autocorrelation also include two forms: low-high (L-H) outliers
occur when the focal observation displays a low value, but its surroundings have high values; and high-low (H-L) outliers occur when the focal observation shows a high value, but its neighbors have low values. The mechanism to do this is like the one used in the Global Moran’s I but applied in this case to each observation. To focus on the areas exhibiting statistical significance, the significance filter was set to 0.01 for each LISA cluster map. 

$Gi^*$.

The other local measure, Getis-Ord $Gi^*$, used the same spatial weights matrices and was computed in GeoDa software with the Local G* tool. This tool works by looking at each observation within the context of neighboring observations. The $Gi^*$ statistic includes the focal point in its calculation and thus lends itself to studies of clustering since a cluster usually contains its focus as a member of the cluster (Getis & Ord, 1992; Ord & Getis, 1995). To be a statistically significant hot (cold) spot, a feature will have a high (low) value and be surrounded by other features with high (low) values as well. The local sum for a feature and its neighbors is compared proportionally to the sum of all features; when the local sum is very different from the expected local sum, and when that difference is too large to be the result of random chance, a statistically significant z-score results. For statistically significant positive z-scores, the larger the z-score is, the more intense clustering of high values (hot spot). For statistically significant negative z-scores, the smaller the z-score is, the more intense is the clustering of low values (cold spot). Hot spots or cold spots identified by this statistic can be interpreted as clusters or indications of spatial nonstationary. Because $Gi^*$ is another local statistic, a cluster map was created for each metal and the significance filter was set to 0.01 to assess statistical significance.

After establishing the presence of spatial autocorrelation in each of the metal concentrations, both globally and locally, my next step was to create a series of maps using
spatial interpolation. While it is often useful to use only known point observations and evaluate spatial patterns of those measurements, another goal may be to create a “surface” of those variable(s) across an entire study region. This process of spatial interpolation uses locations with known, sampled values of a phenomenon (i.e., metal concentration) to estimate values at unsampled locations over a continuous spatial field. Spatial interpolation requires two primary assumptions: (a) spatial autocorrelation is present in the values of a variable, and (b) data values for a variable are normally distributed. Since the values for each metal showed both global and local spatial autocorrelation, the first assumption for spatial interpolation was met. Examining the descriptive statistics of each metal revealed that values for all metals were positively skewed. Therefore, a log10 transformation was applied to make the values of each metal more normal and satisfy the second assumption.

**Kriging**

Spatial interpolation can usually be grouped into two categories: deterministic and statistical methods. Deterministic approaches, such as Thiessen polygons or inverse distance functions, rely on mathematical methods to carry out interpolation. Most of these methods take account of systematic variation only and disregard the errors of prediction. Kriging, on the other hand, is a statistical approach and overcomes the weaknesses of mathematical interpolators. It makes the best use of existing knowledge by taking account of the way a phenomenon varies across space through the semivariogram function.

The semivariogram is a visual depiction of the covariance exhibited between each pair of points in the sampled data. For each pair of points in the sampled data, the semi-variance (a measure of the half mean-squared difference between their values) is plotted against the distance, or lag, between them. The experimental semivariogram is the plot of observed values, while the theoretical semivariogram is the distributional model that best fits the data. Semivariogram
models are drawn from a limited number of functions, including linear, spherical, circular, exponential, and Gaussian. The choice of a semivariogram model is fundamentally user-defined, yet software programs (e.g., R or ArcMap/ArcGIS Pro) can often help define best-fitting models through various means.

The semivariogram measures spatial autocorrelation and determines how much influence a known point has on an unknown point as the distance between the two increases. In other words, spatial interpolation through kriging is based on the spatial arrangement of empirical observations rather than on a presumed model of spatial distribution. Kriging provides not only predictions but also generates estimates of the uncertainty surrounding each interpolated value. Kriging can, therefore, be regarded simply as a method of local weighted moving averaging of the observed values of a random variable within a neighborhood. Kriging will in general be less effective than simpler methods of interpolation if there is little spatial autocorrelation among the sampled data points. That is, kriging performs better when values co-vary across space and spatial autocorrelation is more pronounced. If there is at least moderate spatial autocorrelation, however, kriging can be a helpful method to preserve spatial variability that would be lost if using a simpler method.

Kriging can be understood as a two-step process: first, the spatial covariance structure of the sampled points is determined by fitting a semivariogram; and second, weights derived from this covariance structure are used to interpolate values for unsampled points across the spatial field/study region. In short, the kriging weights are calculated such that points nearby to the location of interest are given more weight than those farther away. Clustering of points is also considered, so that clusters of points are weighted less heavily. This helps reduce bias in the predictions. The kriging predictor is an optimal linear predictor and an exact interpolator,
meaning that each interpolated value is calculated to minimize the prediction error for that point. The value that is generated from the kriging process for any sampled location will be equal to the observed value at this point, while the interpolated values will be the best linear unbiased predictors.

Most of the commonly used interpolation methods are based on the same principle, where a predicted value is a weighted average of neighboring points. Weights for each interpolated point are calculated according to the spatial structure of the interpolated location in reference to all the sampled points. The weights are determined from the semivariogram based on the spatial structure of the data, and are applied to the sampled points according to the following formula:

\[
\hat{Z}(x_j) = \sum_{i=1}^{n} \lambda_i z(x_i)
\]

Where the value of the predicted point, \(\hat{Z}(x_j)\), is equal to the sum of the value of each sampled point, \(z(x_i)\), times the unique weight of that point, \(\lambda_i\). The covariance matrix from the estimated semivariogram is used to calculate the weights, which will differ slightly based on the type of kriging being conducted.

Kriging interpolation maps were created in ArcGIS Pro using the Geostatistical Wizard tool. Within the Geostatistical Wizard, the Kriging/CoKriging option was selected from the list of available Geostatistical Options and then Prediction was chosen for Ordinary Kriging. These same basic settings were applied to all models for each of the six metals. Four models were run for each metal using different semivariogram functions: circular, spherical, Gaussian, and exponential. In each case, the anisotropy option was selected to account for changes in spatial autocorrelation based on distance and direction (ESRI, 2022c). The Optimize Model option was selected and applied to each model run. To create the neighborhood set used by the kriging
interpolator, the following parameters were chosen: standard neighborhood type, 5 maximum
neighbors, 2 minimum neighbors, and sector type of 4 sectors with 45° offset. This procedure
resulted in a total of 24 kriging models across the six priority metals.

The 24 models were assessed to identify which semivariogram function was most
appropriate for each metal. Several evaluation criteria were considered to determine model
accuracy (in order of importance): the smallest root-mean-square error (RMSE); a standardized
RMSE closest to 1; an average standard error (SE) near RMSE; and a standardized mean near
zero. The summary statistics of all semivariogram functions for each metal are presented in
Tables 4-9. Maps were created using the most appropriate semivariogram function for each metal
and these maps are displayed in Figures 32-37.
Chapter Seven: Results
Point pattern maps

Following the steps outlined in the above analysis flowchart, the first maps that I created were the point pattern maps seen in Figures 13-18. These point pattern maps were critical in gaining an understanding of the general patterns early into investigating the data. From these maps, a few key points of interest emerge. The first notable pattern across all six metals is the concentration of low values along the West Duwamish Greenbelt (WDG). The WDG is “city’s largest remaining contiguous forest”, which spans “over 500 acres and spans over four miles north to south and west to east from a steep slope in the Delridge area in West Seattle to the Duwamish Waterway” (West Duwamish Greenbelt Trails, 2020). Across all six metals there appears to be an almost ‘wall’ of low metal concentrations running alongside the WDG area. Cadmium is the only notable exception to this blockade of low values, with a few points of higher concentration on the west side of the Greenbelt. Other metals tend to have higher concentration on the east side of the Greenbelt, though notably both nickel and lead appear to maintain relatively low concentration values in the entire area bordering the forest.

The southern region of the study site also shows relatively low concentration values across all metals. Nickel and lead in particular have notably low levels in the South Park area. The remaining four metals also tend to show lower concentrations here, but these do have some points of higher concentration near the South Park area.

At the center of the study area is where the majority of high values are found for each metal. It should be noted that cadmium is an exception – while it is more highly concentrated in the center of the map as is the case with the other metals, its concentration follows a unique pattern. This is seen in the presence of high values in the Greenbelt, but also is notable in the rather small clustering of high values in the center of the map when compared to other metals.
where high values are abundant. That said, the two highest points of cadmium concentration can be found in the center of the map as is the case with the other metals. Lead, chromium, and arsenic show the highest concentration at the epicenter of the study site, but this trend of clustered high concentration towards the center of the map remains true even for nickel, cobalt, and cadmium.

Arsenic shows the clearest pattern of continuous high concentrations stretching up into the center-north area of the map. The other metals (apart from cadmium) follow this same pattern though some to lesser extent. In the case of arsenic, there is an obvious trend of high concentrations running throughout the center of the map with the highest values in the center and stretching up to the northern tip of the study site. This remains true of the other metals, though their point pattern maps are slightly less pronounced in this trend. Cadmium remains unique in its pattern and does not show the high concentration clustering in the center north as the other metals do. This pattern of higher values stretching from the center of the map up to the north was expected, given that this is the area where three of the four suspected polluters are located: Seattle Iron and Metals, Bloch Steel Industries, and Ardagh Group. General Recycling of Washington had not yet been identified as a potential polluter at the time of the point pattern map creation.

The final area of note is the northeast portion of the study site near the Jefferson Park Golf Course. This area is like WDG in that there are very low concentrations of all metals here with very few exceptions. There is one notably high instance of chromium in one sample, but overall, the area is dominated by either low or very low concentrations. This pattern is exceptionally important to take into consideration as the Beacon Hill air monitoring site is located within the Jefferson Park Golf Course (to the west side of Beacon Avenue South). This
almost uniform pattern of low concentrations surrounding the monitor is critical, particularly when considering the pattern of high metal concentration of all six varieties in the study site’s center.

It is important to note though that while these point pattern maps do give some indication of potential spatial autocorrelation at play, there is no definitive evidence of spatial dependence using only the patterns present in the point pattern maps. Rather, the point pattern maps give a baseline understanding of the overall concentration trends within the study area. ‘Clustering’ mentioned in relation to these maps does not refer to any statistical measurement of spatial clustering, but rather is used in the colloquial sense of the term. Tests for spatial clustering follow this in the form of Moran’s I and Gi*.

It should also be noted that the data used here is untransformed, but the amount of metal present in the samples should be understood as relative. Because moss is being used only as an indicator and not an exact measure of metal concentration, the amount of metal present is being used only to compare to itself rather than to stand as a definitive measure of the exact amount of pollution in the Valley. Still, these maps are critical in visualizing potential trends of pollution and setting up for the more sophisticated spatial autocorrelation testing that follows.
Figure 13. Point pattern map of arsenic concentration in the Duwamish River Valley.
Figure 14. Point pattern map of cadmium concentration in the Duwamish River Valley.
Figure 15. Point pattern map of chromium concentration in the Duwamish River Valley.
Figure 16. Point pattern map of cobalt concentration in the Duwamish River Valley.
Figure 17. Point pattern map of lead concentration in the Duwamish River Valley.
Figure 18. Point pattern map of nickel concentration in the Duwamish River Valley.
Global Moran’s I

<table>
<thead>
<tr>
<th>Metal</th>
<th>First Peak (meters)</th>
<th>z-score</th>
<th>Moran’s I</th>
<th>Max Peak</th>
<th>z-score</th>
<th>Moran’s I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>600</td>
<td>13.235</td>
<td>0.359</td>
<td>1100</td>
<td>15.001</td>
<td>0.221</td>
</tr>
<tr>
<td>Cadmium</td>
<td>600</td>
<td>7.288</td>
<td>0.186</td>
<td>1000</td>
<td>8.181</td>
<td>0.125</td>
</tr>
<tr>
<td>Chromium</td>
<td>750</td>
<td>11.857</td>
<td>0.2592</td>
<td>900</td>
<td>12.337</td>
<td>0.222</td>
</tr>
<tr>
<td>Cobalt</td>
<td>500</td>
<td>10.959</td>
<td>0.353</td>
<td>750</td>
<td>12.832</td>
<td>0.273</td>
</tr>
<tr>
<td>Lead</td>
<td>850</td>
<td>14.55</td>
<td>0.275</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Nickel</td>
<td>500</td>
<td>9.588</td>
<td>0.194</td>
<td>900</td>
<td>11.781</td>
<td>0.194</td>
</tr>
</tbody>
</table>

Table 2. Global Moran’s I diagnostics.

Table 2 contains the results of the spatial weights matrix testing using the Incremental Spatial Autocorrelation tool. As mentioned, each metal was tested several times using slightly altered distance variables to find the most appropriate peak for each. Figure 19 shows the charts of the spatial autocorrelation over the distance of the study area, with the peaks highlighted in blue. Nickel and cobalt have the shortest peak distance at 500m, whereas lead had the largest at 850m. Examining the graphs, it becomes very clear that utilizing one single distance band for all metals would be far too generalized to perform subsequent tests to their highest optimization. In this case, the distance at which spatial processes promoting clustering are most pronounced is varied enough to require each metal be treated separately, and thus from this test it was decided that 4 separate distance bands would be used for the subsequent analysis: 500m, 600m, 750m, and 800m.
Figure 19. Graphs of spatial autocorrelation by distance for As, Cd, Cr, Co, Pb and Ni
Local Moran’s I (LISA)

Figures 20-25 show the results of the Local Moran’s I tests. In the case of lead, there is a clustering of high-high values near the center of the study area. This pattern of centralized high-high values is seen throughout each of the five metals but is most pronounced in the lead map. In terms of high-high clustering, arsenic shows the furthest range of H-H values, stretching from the middle of the map up into the northern and north-west corners. This H-H clustering pattern in the north-west is notable as it is also seen (to a lesser degree) in the lead, cobalt, and chromium map, all of which have a central cluster of H-H in the center of the map and at least one point of H-H in the north-west.

It was because of these H-H points in the north-west that a fourth potential polluter was located in the Valley. Seattle Iron and Metals, Bloch Steel Industries and Ardagh Group could explain the clustering of high values in the center of the Valley, it seemed unlikely that they would be the cause of clustering in the small area on the opposite side of the river. This area was identified as having some points of high concentration in arsenic, chromium, and lead in the point pattern map, and using LISA mapping revealed statistically significant clustering of chromium and arsenic. Thus, following investigation into industry with metal waste located in this northwest corner, General Recycling of Washington was added to the list of potential polluters within the DRV.

As mentioned, high-high positive spatial autocorrelation is clustered in the center of the study area across all six metal types. Notably, low-low concentrations tend to also be consistent throughout each of the maps, hinting at potential shared patterns between all six pollutants. In the case of low-low clustering, this occurs primarily in the south-west and north-east for each metal type. This low-low clustering is especially notable in the north-east area of the map as this
clustering of low pollutant values is located near the Beacon Hill monitor. This indicates that there is a concentration of low pollutant values near this monitor, which was expected given the consistently cleaner air monitor readings from Beacon Hill as opposed to the monitors down in the base of Valley itself. Once again, this pattern was seen in the point pattern analysis, but the results of the LISA and Gi* mapping indicate that there is spatial autocorrelation underlying the patterns of low concentrations near the Beacon Hill monitoring site.

Notably, there are a few low-highs within the central cluster of high-high values within the case of lead. This indicates that are some points with low lead concentration surrounded by neighbors of high concentration. These low-high points (as well as the few high-low points) indicate that there is negative spatial autocorrelation occurring in these areas. Lead shows the highest amount of negative spatial autocorrelation, with a total of 14 significant points indicating negative autocorrelation. The next highest was chromium, with 12 points indicating negative spatial autocorrelation. All four remaining metals have less the 4 instances of significant negative spatial autocorrelation (both L-H and H-L). Ultimately, each of the six metals displays an overall trend of positive spatial autocorrelation, with negative autocorrelation most pronounced in the lead and chromium samples.
Figure 20. Local Moran’s I map of arsenic concentration in the Duwamish River Valley.
Figure 21. Local Moran’s I map of cadmium concentration in the Duwamish River Valley.
Figure 22. Local Moran’s I map of chromium concentration in the Duwamish River Valley.
Figure 23. Local Moran’s I map of cobalt concentration in the Duwamish River Valley.
Figure 24. Local Moran’s I map of lead concentration in the Duwamish River Valley.
Figure 25. Local Moran’s I map of nickel concentration in the Duwamish River Valley.
The results of the Gi* mapping are shown in Figures X-X. Many of the patterns seen in the LISA maps are present here, such as the pronounced pattern of high values stretching from the center of the map up to the center north in the case of arsenic. As, Pb, and Cd only have statistically significant high values to the north with no high values stretching to the south into the South Park community. This is not the case for cobalt, nickel, and chromium, all of which show high values to the south.

The pattern of nickel in Gi* mapping is of particular interest, as it shows the lowest number of significant high values (4 high values total). One of these values is isolated from the rest, sitting to the north. The remaining three points are clustered further to the south, but still close to the center of the study area where much of the high value clustering of other metals occurs. This indicates that while there might be less clustering of high values, the positioning of these high values still follows a similar pattern of clustering in the middle of the map that the other metals exhibit. All the remaining metals exhibit clustering in the center of the map, though slightly to the north of the nickel cluster.

Without exception, the Beacon Hill area has clustering of low values. Every metal shows this same pattern, though the low clustering is most prominent in arsenic, chromium, and lead. Other cold spot clustering is seen in the WDG area which also has a similar pattern of low value clustering across each metal type. In the case of As, Pb, Cd, and Co, low values are concentrated to the south whereas Ni and Cr have some cold spots further to the north of the WDG. The final cold spot pattern to make note of is the few cold spots to the east of the WDG area seen in Cd, Co, Ni, and Pb. Though there is no obvious cause for these few cold spots, it is worth noting their presence in the South Park area.
Figure 26. Gi* map of arsenic concentration in the Duwamish River Valley.
Figure 27. Gi* map of cadmium concentration in the Duwanish River Valley.
Figure 28. Gi* map of chromium concentration in the Duwamish River Valley.
Figure 29. Gi* map of cobalt concentration in the Duwamish River Valley.
Figure 30. Gi* map of lead concentration in the Duwamish River Valley.
Figure 31. Gi* map of nickel concentration in the Duwamish River Valley.
Table 3 displays the summary statistics of the raw data collected from the moss samples. This data is important to gather a general idea of the amount of pollution potentially present across the DRV. But as has been stated previously, these numbers should not be considered as definitive amounts of pollution concentration within the Valley. Because moss is not considered a precise measuring tool but rather as an indicator, it is critical to be cautious of drawing conclusions from the raw data alone. Still, it is important to gather a full snapshot of the area to get a general idea of the levels of pollution that may be present.

Further, the summary statistics above are important in testing the normality of the data. Most importantly here is the measure of skewness, which is positive in all cases. Because of this, I decided that moving forward with kriging would involve a log10 transformation of all of the data. Thus, the kriging maps displayed on the following pages are informed by this measure of skewness.
### Table 4. Summary statistics of four semivariogram models of arsenic.

<table>
<thead>
<tr>
<th>Semivariogram Function (ARSENIC)</th>
<th>Distance Lags</th>
<th>Model Bias</th>
<th>Accuracy</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circular</strong></td>
<td>12</td>
<td>-0.0002</td>
<td>0.0017</td>
<td>0.1773</td>
</tr>
<tr>
<td><strong>Spherical</strong></td>
<td>12</td>
<td>-0.0006</td>
<td>-0.0005</td>
<td>0.1719</td>
</tr>
<tr>
<td><strong>Gaussian</strong></td>
<td>12</td>
<td>-0.0004</td>
<td>-0.0012</td>
<td>0.1699</td>
</tr>
<tr>
<td><strong>Exponential</strong></td>
<td>12</td>
<td>-0.0008</td>
<td>-0.0008</td>
<td>0.1776</td>
</tr>
</tbody>
</table>

### Table 5. Summary statistics of four semivariogram models of cadmium.

<table>
<thead>
<tr>
<th>Semivariogram Function (CADMIUM)</th>
<th>Distance Lags</th>
<th>Model Bias</th>
<th>Accuracy</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circular</strong></td>
<td>12</td>
<td>0.0022</td>
<td>0.0086</td>
<td>0.2407</td>
</tr>
<tr>
<td><strong>Spherical</strong></td>
<td>12</td>
<td>0.0013</td>
<td>0.0050</td>
<td>0.2413</td>
</tr>
<tr>
<td><strong>Gaussian</strong></td>
<td>12</td>
<td>0.0037</td>
<td>0.0122</td>
<td>0.2412</td>
</tr>
<tr>
<td><strong>Exponential</strong></td>
<td>12</td>
<td>0.0008</td>
<td>0.0024</td>
<td>0.2441</td>
</tr>
<tr>
<td>Semivariogram Function (CHROMIUM)</td>
<td>Distance Lags</td>
<td>Model Bias</td>
<td>Accuracy</td>
<td>Precision</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---------------</td>
<td>------------</td>
<td>----------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td># of Lags</td>
<td>Lag Size</td>
<td>Mean</td>
<td>Mean Std.</td>
</tr>
<tr>
<td>Circular</td>
<td>12</td>
<td>123.6377</td>
<td>-0.0007</td>
<td>-0.0009</td>
</tr>
<tr>
<td>Spherical</td>
<td>12</td>
<td>125.5977</td>
<td>-0.0008</td>
<td>-0.0004</td>
</tr>
<tr>
<td>Gaussian</td>
<td>12</td>
<td>86.1081</td>
<td>0.0005</td>
<td>0.0026</td>
</tr>
<tr>
<td><strong>Exponential</strong></td>
<td><strong>12</strong></td>
<td><strong>315.1953</strong></td>
<td><strong>-0.0017</strong></td>
<td><strong>-0.0035</strong></td>
</tr>
</tbody>
</table>

*Table 6. Summary statistics of four semivariogram models of chromium.*

<table>
<thead>
<tr>
<th>Semivariogram Function (COBALT)</th>
<th>Distance Lags</th>
<th>Model Bias</th>
<th>Accuracy</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of Lags</td>
<td>Lag Size</td>
<td>Mean</td>
<td>Mean Std.</td>
</tr>
<tr>
<td>Circular</td>
<td>12</td>
<td>123.6377</td>
<td>-0.0010</td>
<td>-0.0007</td>
</tr>
<tr>
<td>Spherical</td>
<td>12</td>
<td>133.7533</td>
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<td>-0.0025</td>
</tr>
<tr>
<td>Gaussian</td>
<td>12</td>
<td>86.1081</td>
<td>-0.0001</td>
<td>0.0006</td>
</tr>
<tr>
<td><strong>Exponential</strong></td>
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<td><strong>280.1233</strong></td>
<td><strong>-0.0023</strong></td>
<td><strong>-0.0043</strong></td>
</tr>
</tbody>
</table>

*Table 7. Summary statistics of four semivariogram models of cobalt.*
<table>
<thead>
<tr>
<th>Semivariogram Function (LEAD)</th>
<th>Distance Lags</th>
<th>Model Bias</th>
<th>Accuracy</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of Lags</td>
<td>Lag Size</td>
<td>Mean</td>
<td>Mean Std.</td>
</tr>
<tr>
<td>Circular</td>
<td>12</td>
<td>202.9173</td>
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<td>0.0004</td>
</tr>
<tr>
<td>Spherical</td>
<td>12</td>
<td>231.9425</td>
<td>0.0001</td>
<td>0.0008</td>
</tr>
<tr>
<td>Gaussian</td>
<td>12</td>
<td>74.1569</td>
<td>0.0014</td>
<td>0.0050</td>
</tr>
<tr>
<td><strong>Exponential</strong></td>
<td><strong>12</strong></td>
<td><strong>374.7296</strong></td>
<td><strong>-0.0001</strong></td>
<td><strong>1.0664</strong></td>
</tr>
</tbody>
</table>

*Table 8. Summary statistics of four semivariogram models of lead.*

<table>
<thead>
<tr>
<th>Semivariogram Function (NICKEL)</th>
<th>Distance Lags</th>
<th>Model Bias</th>
<th>Accuracy</th>
<th>Precision</th>
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</thead>
<tbody>
<tr>
<td></td>
<td># of Lags</td>
<td>Lag Size</td>
<td>Mean</td>
<td>Mean Std.</td>
</tr>
<tr>
<td>Circular</td>
<td>12</td>
<td>123.6377</td>
<td>-0.0001</td>
<td>-0.0016</td>
</tr>
<tr>
<td>Spherical</td>
<td>12</td>
<td>124.6138</td>
<td>-0.0007</td>
<td>-0.0005</td>
</tr>
<tr>
<td><strong>Gaussian</strong></td>
<td><strong>12</strong></td>
<td><strong>90.9811</strong></td>
<td><strong>0.0006</strong></td>
<td><strong>0.0037</strong></td>
</tr>
<tr>
<td>Exponential</td>
<td>12</td>
<td>284.5640</td>
<td>-0.0010</td>
<td>-0.0011</td>
</tr>
</tbody>
</table>

*Table 9. Summary statistics of four semivariogram models of nickel.*
Tables 4-9 display the kriging diagnostics for each of the six metals. Each metal was tested with 4 semivariograms, and the results of each model (circular, spherical, Gaussian, and exponential) are all displayed within the appropriate metal table. Ultimately, exponential fit the most metals (chromium, cobalt, and lead), with Gaussian being the second most popular (arsenic and nickel). Cadmium was best fit by a circular function.

The root mean squared (RMSE) remained low for all six models and was relatively similar for each model for each type of metal. This indicates a high level of accuracy in the chosen models. Further, the RMSE standardized was close to 1 in every instance, with the lowest being 0.9786 and the highest at 1.0999 within all models not merely the ones selected for each metal. This confers a high degree of accuracy of standard errors.

The mean standardized gives an average of standardized errors, and ideally should be as close to zero as possible. The largest mean standardized for one of the selected models is cadmium with a 0.0086. This low number for the cadmium circular model (and even lower mean standardized for the other five metals) indicates a low level of bias within the model.

Finally, the average standard error was incredibly close to RMSE in the models chosen. The largest difference in RMSE and average SE in a chosen model is 0.0185 (cadmium). This is an incredibly low value of difference, indicating that the models selected are not only accurate, but also precise.

The results of the kriging process are displayed in figures X-X. In each of the six metals, there are between 2-3 ‘hot spots’, which is to say areas that are predicted to have the highest level of pollution. These areas are indicated in red. The high predicted concentrations stretch from the center of the study site up towards the center north in all six metals. While there are
many nuances discussed below, the overall trend of predicted pollution in the DRV is very clearly centered in the heart of the study area, stretching both north and south along the waterway. In general, these high predicted concentrations tend to be more prominent in the north than the south.

Five of the six metals (cadmium excluded) share one hotspot located in the center of the map which follows the trends seen in the previous mapping. Though the exact size and shape of the area varies between metals, what remains consistent is the proximity to Seattle Iron and Metals. Seattle Iron and Metals is fully encompassed by the hot spot in each of the five metals, save arsenic. In the case of arsenic, while the facility is not wholly located within the area of highest concentration, it is on the border of this area of highest concentration.

A similar pattern to this one occurs further to the north surrounding another point of interest: Bloch Steel Industries. In four of the six kriging maps, Bloch Steel Industries is either fully encompassed by or immediately next to an area of the highest metal concentration prediction. The only exceptions to this are lead, which has another hot spot to the north and cadmium, which exhibits a unique pattern in comparison to the other metals.

In the case of cadmium, there are a few unique features worth highlighting. Cadmium has the smallest areas of the highest concentration when compared to the other metals. The position of these areas also varies, with both of the predicted areas of highest concentration being very close to the Ardagh Group facility. Additionally, cadmium has a unique, very small hot spot that is also near the Ardagh Group (though it is worth noting that this area is located on the opposite side of the Duwamish River as the Ardagh Group facility).
Chromium also exhibits a unique character when it comes to high concentration areas. In the northwest corner of the map, there is a hot spot located to the west of General Recycling of Washington. This aligns with the observed L-H spots on the chromium LISA map, as well as the instances of high value clustering shown in the Cr Gi* map. Every other metal also has high predicted values in this area, but chromium has the highest predicted concentrations in this area, relatively speaking.

Just as the highest concentrations followed a general trend, so does an overall pattern emerge across all six metals in terms of low concentration. As expected from all previous mapping, the Beacon Hill area is almost entirely encompassed by the lowest concentration prediction class for all six metals. The only exception to this is cadmium, which has a few areas of yellow (middling amount of predicted pollution) near Beacon Hill, but even Cd remains largely low in the area.

Another area of expected low concentrations is shown to be along the Western Duwamish Greenbelt. The forest has a wall of low values stretching almost the entirety of the western edge of the study area. Once again, cadmium shows some slight variation from the overall trend of the other metals with a few areas of middling concentration predicted in the WDG area. This follows the unique pattern of high concentration points on the west side of the WDG observed in the LISA and Gi* cadmium maps.

Finally, the southern portion of the study site near the South Park area shows a generally low predicted pollution for all of the six metals. Ni, Co, and As have slightly higher predicted levels when compared to Cd, Cr, and Pb though these levels are still relatively low.
Ultimately, the results of the kriging follow along with the pattern seen in the initial point pattern maps as well as the trends seen in the LISA and Gi* maps. Generally speaking, there are higher predicted concentrations of all six metals in the center of the study area near Seattle Iron and Metals. This area of high pollution stretches up to the northern center of the map, and down slightly into the South Park area to varying degrees. To the north-west, another predicted hot spot emerges near General Recycling of WA. While more pronounced in some metals, this hot spot appears in all six metals. Also shared between all metals are the areas of low pollution found in the Western Duwamish Greenbelt. And perhaps most importantly is the shared cold spot near Beacon Hill.
Figure 32. Kriging surface of arsenic concentration in the Duwamish River Valley.
Figure 33. Kriging surface of cadmium concentration in the Duwamish River Valley.
Figure 34. Kriging surface of chromium concentration in the Duwamish River Valley.
Figure 35. Kriging surface of cobalt concentration in the Duwamish River Valley.
Figure 36: Kriging surface of lead concentration in the Duwamish River Valley.
Figure 37. Kriging surface of nickel in the Duwamish River Valley.
Chapter Eight: Discussion and Future Directions
To open this thesis, I began with six key questions which I believe have been answered though the course of this study. The first question “Can neighborhood scale pollution monitoring via moss be an effective tool for identifying patterns of localized air pollution?” has shown to be a resounding yes. This thesis as well as the studies before it shows that moss can be exceptionally effective in serving as a monitor for air pollution. The degree of success is demonstrated in the answers to the remaining five questions.

The second question posed asked, “What are the benefits and drawbacks to this type of monitoring?” After completing this study and reviewing other moss study literature, I firmly believe that the benefits of moss monitoring far outweigh the potential pitfalls. For example, one major potential drawback of moss monitoring is the fact that moss is not everywhere that may need air monitoring. Mosses “have ubiquitous geographic occurrence, which includes the polar regions” (Chaudhuri & Roy, 2023, p. 5; see Cowden et al., 2015; Cannone et al., 2013). This means that a suitable species of moss should likely be present wherever one wishes to monitor, though there may be factors affecting the availability of adequate monitor specimens. Outside of the potential for biological factors to rid an area of moss, so too can human development wipe out the potential samples in an area and in many cases may make reaching moss impossible. Fencing, private property, and building developments are all challenges that may arise when attempting to set up a moss study. And yet moss remains resilient in the face of complications.

One limitation of this form of moss monitoring presented in this thesis is that it was a “passive” type of monitoring. This means we relied on moss collected from its naturally occurring environment and tested for metals. There is also a great deal of potential in more “active” monitoring style which involves the use of transplanted moss from other locations in
moss bags as opposed to relying on already present moss (Chaudhuri & Roy, 2023). Though far more labor intensive than passive monitoring, active moss monitoring may be one way to overcome the potential challenges causing a lack of available samples either due to scarcity or inability to sample in certain areas.

Active monitoring has proven itself to be an effective and popular method of monitoring in several applications such as monitoring traffic related air pollution and was even used in a sixteen yearlong pollution monitoring operation of an oil refinery (Vuković, 2015; Rivera, 2011; De Agostini, 2020). Though active monitoring does have some drawbacks such a lack of standardized protocol in the literature as pointed out in Temple et al.’s review of 112 papers using active biomonitoring, it is still a viable option for instances in which a passive approach is not feasible. This means that the moss model is not only cheaper, but also can be far more flexible than traditional monitoring.

Another downside of moss monitoring is it has no temporal measurement (Bargagli, 2016). Regulatory air monitors also track time. Moreover, other researchers recommend combining moss monitoring with other background monitoring approaches. For example, Conti and Cecchetti’s 2001 review of lichen as a biomonitor suggests, it is necessary to define the background levels of pollution in an area. This allows for a measure of the actual pollution within an area as compared to the surrounding environment (Conti & Cecchetti, 2001). Moss monitoring is best as a complement, not as a replacement, to traditional air monitoring.

In the case of moss monitoring, the pros far outweigh the cons. Moss monitoring remains exceptionally cheaper than stationary air monitoring (Donovan et al., 2016; Steinnes et al., 2011; Lazo et al., 2019). This lower price tag is even more important when screening air pollution from a justice angle as was the intention in reviewing the DRV. Conti & Cecchetti’s (2001) review
points out that passive monitoring is especially appealing to regulatory authorities in “developing economies” that are already facing considerable hardship when it comes to obtaining the resources to put together an adequate air monitoring systems. Moss is a powerful tool for air monitoring that can be employed both in the United States to fill in the Air Quality Management System’s (AQMS) gaps unaddressed by the Clean Air Act, but also as a naturally occurring way to bridge the shortcomings of regulatory and financial restraints in communities across the globe.

**AQMS Deficiencies**

The third question I posed at the start of this thesis was “are there spatial clusters of toxic air pollution in the Duwamish River Valley?” As shown in the spatial interpolation maps, there are hot spots of toxic air pollution within the Duwamish River Valley. The Global Moran’s I testing confirmed the suspicion set on by the point pattern maps: there is spatial autocorrelation present in the DRV. But as stressed in discussing Global Moran’s I previously, knowing that there are hot spots in the Duwamish River Valley is not enough. Instead it is critical to visualize where this pollution is located.

This leads me to my fourth question, “If so, what do these patterns look like and where are they located?” The LISA and Gi* maps were able to show in which areas this spatial autocorrelation occurred and if the concentrations tended towards hot or cold spots. The initial point pattern maps hinted at some potential for spatial clustering of air pollution. These maps allowed me to take stock of general trends present in the Valley, and brough particular attention to the center corridor where three potential polluters were located. But while a useful tool for preliminary exploration, the point pattern maps are not sufficient to prove the existence of spatial autocorrelation. This instead was done using spatial analysis.
Though the six metals did diverge from one another in a few places, there are still large overarching trends shared by each metal. The most prominent pattern is the areas of highest predicted concentration being in the center of the study site and running up to the north alongside the waterway. Major hotspots for all six metals were located in the center of the DRV, indicating that this area is one of the highest in terms of all metal pollution types studied. Though there are some variations in the exact size, shape, and location of these highest concentration areas there is an undeniable trend of higher pollution within the center of the Valley. The second area of shared high concentration was to the northwest, near the river itself.

Complimenting this pattern of hotspots in the heart of the DRV is the shared pattern of cold spots to the east and west. For all metals, there was a significant area of low pollution values to the west where the Western Duwamish Greenbelt is located. This forest has some of the lower pollution values recorded. Cadmium was one of the few exceptions to the block of low values, though its behavior differs notably from the other metals in most areas. One such variation is seen in having some of the only samples of high concentration to the west of the Greenbelt. Cadmium also had much smaller hotspots than the other metals and tended to be in slightly different positions than the other metals. Yet despite these differences, the overall patterns exhibited by cadmium still fall mostly in line with the trends seen in the five other metals. The abnormalities in cadmium reveal that despite the different behavior of certain metals, the overall trend of pollution in the DRV is incredibly similar across all six types. The presence of high concentrations of pollution in the center of the Valley proper remains consistent across all metals studied despite small nuances across each pollutant.

Perhaps the most telling area is the collective cold spot near Beacon Hill. All the metals show low values almost the entire area surrounding the area. Once again, cadmium remains an
exception in this case, though the predicted numbers are still quite low compared to the rest of the cadmium kriging map. This shared cold spot further emphasizes the point that the area of Beacon Hill is not the same as the area within the Valley proper. The difference in elevation as well as the positioning of the Beacon Hill makes a serious impact on the airshed and the ability of the area around Beacon Hill to record data that is accurate to the Valley itself.

The shared trends of hot and cold spots feeds into my fifth: “If present, what does the spatial pattern of pollution in Duwamish River Valley show about the potential polluters in the area?” The presence of a hot spot corridor through the center of the study site coincides with the locations of three potential polluters that have previously been identified: Seattle Iron and Metals, Bloch Steel Industries, and Ardagh Group. This is not to say that all the pollution recorded and predicted in this corridor are a direct result of only these three industries; however, given the history of improper industrial waste disposal as well as the numerous fires and other accidents that occur at these facilities, it is worth noting their presence at the center of the predicted pollution hot spots.

The final potential polluter that was identified through this process was General Recycling of Washington. When initially identifying potential polluters using just point pattern maps, the northeast area of the map was not seriously considered as being a hot spot of pollution because the obvious clustering of high values at the center of the Valley drowned out some of the detail within the preliminary maps. It was not until the LISA maps that another polluter was considered. It was only through spatial autocorrelation testing that I was able to create such a nuanced map of the pollution landscape in the Duwamish River Valley.

Beyond further demonstrating the efficacy of moss monitoring as a method, this discovery of a fourth potential polluter is a clear example of why finer scale monitoring is so
important. While identifying a potential polluter is a useful piece of information, what is more important is that this demonstrates how extremely complex air pollution can be. Coarser scale monitors are generally able to capture overall trends in air quality, but there is a great deal of complexity that can be easily missed when not using a fine scale approach. Capturing such localized hot spots would be nearly impossible using the traditional air monitoring method. Air pollution exists with a level of complexity that is extremely difficult to pick up without localized monitoring.

The major trend of pollution found via kriging running through the center of the Duwamish Valley is hardly being picked up by the three monitors present within the Valley. At the very least, what is being picked up is not considered at a level of concern for the Washington Department of Ecology to make serious changes to monitoring in the DRV. This means that despite the evidence of pollution hot spots identified by this thesis, the inadequacy of the AQMS results in communities like the DRV facing decades of unjust environmental hazards.

Further, if the monitoring part of the AQMS system set up by the CAA is unable to fully capture the larger hotspots such as the central trend in the DRV, what chance does it have of identifying even smaller pollution pockets such as the one found near General Recycling of Washington? This particularly small hot spot found here may not be a life-threatening situation for those residents living nearby – with the information gathered from the site, it is difficult to make claims about the severity of the resulting health risk. But that does not mean there is no risk when it comes to even the smallest of hot spots. In the case of some metals such as lead, multiple top medical organizations and publications such as the World Health Organization agree that there is no safe level of exposure (WHO, 2023; Grandjean, 2010; Davenport, 2023). Any amount of lead is a danger to human health, but unfortunately clean air authorities cannot
begin to even assess whether hot spots are a health risk because they are not even aware of their presence due to the outdated system of air monitoring in the United States.

My final question asked “How do the observed trends inform understanding about air monitoring sites in the DRV?” The interpolation maps revealed intriguing spatial patterns surrounding the Beacon Hill monitor. This monitor is the site of most contention given its location far away from the central Valley as well as its continued status as a monitoring site despite other areas being cited as more suitable (Goswami et al., 2002). This, combined with its consistently better readings than the South Park and Duwamish monitors is what made it a focal point of this thesis. And as predicted, the moss samples reveal that the air surrounding the Beacon Hill monitor is extremely dissimilar to the surrounding Valley.

**Beacon Hill’s Blind Spot**

Beacon Hill is a site of cold spots for all metals to varying degrees. For most, this is where the highest levels of low value clustering are found. This means that there are statistically significant differences in the air surrounding the Beacon Hill monitor compared to the air in the Valley. The pollution situation here is quite obviously radically different than the surrounding area as exemplified by the cold spot clustering in each of the analysis maps. The results of my kriging analysis reveal that the Beacon Hill monitor is not at all suitable as an indicator for the overall state of the air in the Duwamish River Valley.

Once again, I would like to emphasize that there is no explicit problem in simply collecting data from Beacon Hill - collecting data at the site is in fact a very good thing. More data gives us a better understanding of pollution across all South Seattle; however, the usefulness of Beacon Hill’s data is limited when it comes to discussions of air quality in the Valley. It becomes downright harmful when this data is averaged with readings from the South Park and
Georgetown monitors. The Beacon Hill site is simply too different to be considered representative of the Valley’s air, and continuing to use it as an indicator is an act of environmental injustice on the part of the EPA and the Washington State Department of Ecology. Using an urban scale monitor to make decisions at a neighborhood level leaves far too much room for pollution hot spots to go unnoticed. The harm being perpetuated by current use of this monitor must be acknowledged by these entities if the Duwamish River Valley community is ever to receive the justice they rightly deserve.

Beacon Hill as a monitoring site is not the issue at hand. Rather, Beacon Hill is just one example of the way that the AQMS created by the CAA is fundamentally unable to provide adequate protections to all people. As it stands, the EPA is failing not only to provide adequate protection but is also failing to honor their own commitments to environmental justice (EPA, 2023f; Clinton, 1994). In the case of the DRV and given the lack of funding to receive new monitors, keeping the Beacon Hill monitor while making no moves to better assess air quality in South Seattle is a further act of environmental injustice being committed by the EPA and the WA Department of Ecology. Beacon Hill’s monitoring site should in no way be shut down or lessened, but the EPA needs to take a critical look at the scale which they are using to approach air monitoring if they wish to make any meaningful steps towards remedying the air pollution problem. In an ideal world, there would be no need to fight for monitors in each community, but the reality of the situation is that funding is limited, and human health is at stake. The current state of the AQMS remains outdated and inflexible, which means that solutions will need to be found itself of traditional means (GAO, 2020). This leaves a handful of viable solutions for the Duwamish River Valley moving forward.
The first and most effective path forward would be a total reassessment by the EPA and the WA Department of Ecology of the methods being used to evaluate air quality in the DRV. The EPA, Department of Ecology, and PSCAA need to seriously consider the critiques of scholars such as Flatt (2015) and Gonzalez (2021) and make strides to fix the problems pointed out by these and numerous other publications. Including the Beacon Hill readings in the assessment of air quality in the Duwamish River Valley is perpetuating environmental injustice and these agencies need to take responsibility for the impact of their decisions on communities like the Valley. The goal for the DRV would be not only to adjust the methods being used to assess the air quality presently, but to continue to work with the community to further improve understanding and treatment of pollution within the area.

While receiving new monitors in the Valley would be a massive win for the community and make keeping an accurate record of air quality much easier, this should not be seen as the ultimate solution. More stationary air monitors can only go so far, even if NAAQS were updated quickly and accurately enough to keep up with health and safety concerns as well as the ever-advancing body of scientific knowledge on air pollution and related hazards. Realistically, it is not feasible to expect that the EPA will begin placing hundreds if not thousands of monitors to cover each community that has been left out. Even were the EPA financially able to provide an abundance of new monitors, the scale at which these monitors operate remains an issue. It has been demonstrated here that even when working properly it is possible for monitors to miss environmental disturbances such as fires on a worryingly regular basis (McLaughlin et al., 2020). New monitors would need to operate far more regularly than the current monitors, and studies into the appropriate placement of such monitors would be critical. Additional tests at finer scales would still be required to ensure that these monitors do not have the same sorts of
massive blind spots as our current system. This would all place a significant financial burden on the EPA, and thus is likely not a feasible solution, at least in the present.

**Community Led and Meaningful EJ Monitoring?**

When it comes to ensuring the safety of the Duwamish River Valley, the solution is what it has always been: the community. The community and its residents should be the primary focus and driver of air pollution policy reform in the DRV and beyond. Fine scale monitoring projects such as this one are one of the only ways for communities to become aware of and gather evidence of pollution hot spots that are simply too small scale for a national network to pick up on. This means that new programs are needed that are not only focused on gathering finer scale data, but also are community driven and directed.

Meaningful involvement is a critical component of environmental justice, and if proper steps are not taken to ensure the involvement of the community there is a high risk of creating even more problems than are being solved. Programs such as the EPA’s loan sensor programs offer a decent framework for how such monitoring should be conducted, but in their current form such programs are at risk of creating just as much injustice as they may solve. So, in their place other solutions such as moss studies offer a potential avenue for change that is far more accessible and easily reproduced on a wide scale. Moss studies have proven to be effective and should be seriously considered as a means to bridge the gaps left behind by the Air Quality Management System created by the CAA.

Though most of this thesis has focused on more contemporary critiques of the AQMS established by the CAA, in closing is important to understand that these criticisms are not new. The AQMS has not *stopped* working in recent years, but rather never managed to begin working as intended. In their 1980 assessment of the Clean Air Act, William Pedersen Jr. outlines the
three key goals of the CAA as they were widely understood in the years following its creation. These goals are as follows: “First, the regulatory system created by the statute should readily incorporate new knowledge as it arises. […] Second, this system should control pollution in the most economically efficient manner. Finally, the mechanical, legal, and procedural workings of the control scheme should strive towards simplicity and consistency” (Pendersen, 1980, p. 1060). Pendersen concludes that the AQMS was failing to meet these goals in the immediate wake of its creation, and I believe that Washington’s AQMS still fails to make good on these objectives.

Often, the EPA does not regularly incorporate new knowledge as it arises, resulting in some cases with lawsuits such as that brought forth by California State Attorney General Becerra in regard to ozone NAAQS lagging behind the available science (Bonta, 2021). Unfortunately, with the way that the US AQMS is currently working it is evident that tightening standards is not enough. In this case, the understanding of what it means to adjust to keep pace with the best available science must be completely changed. Attorney General Becerra’s case is an excellent example of how sticking to the idea that keeping up with science means making adjusting to current systems without much fundamental change is a flawed approach. Tighter ozone standards (or stricter regulations on any pollutant) will hardly solve the issue in communities like the DRV who are not receiving adequate and accurate assessments of their air quality. Stricter NAAQS will be an even less suitable remedy for small cities such as Superior, Wisconsin who lack any air monitoring stations.

Following the guidance of emerging science is not impossible in the case of the US AQMS. But in order to do so, we need to abandon the idea that NAAQS and other caps on pollution emissions will be enough to properly provide clean air to the nation. The science as shown in this thesis and in the work of numerous scholars upon which this work stands shows
that what we need is not merely stricter standards, but genuine change in the way that the EPA and respective state and local entities monitor and assess air pollution. We need to keep updating our understanding of safe pollutant levels, we need more monitors, and we need fine scale analysis. Following the science in this case means taking a much closer look at pollution, literally.

The second goal identified by Pendersen goes hand in hand with this new idea of what it means to be on the cutting edge of science when it comes to clean air policy. As noted numerous times throughout this thesis, stationary air monitoring systems used by the EPA are expensive (Donovan et al., 2016; Gatziolis et al., 2016; Snyder et al., 2013). Further, cases such as the process of siting of the Maple Leaf monitor in South Seattle demonstrate just how tight the budget for new air monitors can be (Goswami et al., 2002). Furthermore, Flatt’s 2015 analysis points out a number of inefficiencies in the handling of regulating air pollution under the CAA. It is not difficult to see that just as Pendersen concluded in 1980, the CAA fails to meet the goals of economic efficiency. Putting aside comparisons to the far cheaper moss study model, the EPA is still grappling with a tight budget and limited resources (Wu et al., 2011; Goswami et al., 2002; Gatizol, 2016). One estimate from Portland, Oregon states that the cost of operating one air toxics monitor is around $40,000 a year (Gatizol, et al., 2016). These monitors are extremely costly, and are failing to meet their goal of adequately monitoring air pollution across the country. In short, the US AQMS is still failing to meet the goal of economic efficiency.

Finally, is the goal of simplicity and consistency. The US and Washington AQMS fails on this front as well. The CAA’s regulatory systems are far from simple, particularly given the complex way that the EPA breaks down responsibility to various entities across its operating regions (EPA, 2017a). This complexity is further compounded in area like South Seattle where
decisions are made to group together findings from various sites to average pollution numbers across a large area. The US and Washington AQMS fails in terms of simplicity, and unfortunately comes up short in terms of consistency as well. Given the numerous instances of industrial disasters as well as day-to-day pollution spikes going entirely undetected either because of a lack of monitor or due to the monitors only operating on certain days/times, it is obvious that the CAA authorities like EPA failed to create a system of consistent quality air monitoring (McLaughlin et al., 2020).

Thus, the US and Washington AQMS in its current state is failing to meet all three of the goals identified by Pendersen’s 1980 report. As it stands, the system fails to provide proper protection for all people. But knowing that there is a problem is not enough to fix it, and so instead the question becomes how to address such issues to ensure that all people are receiving equal and adequate air pollution protection.

**Air Quality Management Systems for Environmental Justice?**

In the conclusion of his article, Victor Flatt suggested that the path forward should be “reform[ing] the federal administrative system for the regulation of residual risks so that it looks like California's or Connecticut's” and that this would ensure “no person in this country would be exposed to levels of air toxics higher than considered safe and acceptable” (Flatt, 2007, p.173). To a degree, I agree with Flatt’s assessment. The EPA and associated entities should be striving to reach the level of regulation and enforcement as states like California, particularly when it comes to the need for consistent and frequent monitoring. However, following the model set out by these states this is not enough to solve the problem.

Gonzalez makes a point in her 2021 article to emphasize that even in these states, there are still numerous areas of toxic air hot spot pollution that are being overlooked by the current
system (Gonzalez, 2021). As Carlson’s 2018 article states “Our current system of air pollution regulation—while enormously successful—may actually mask pollution hotspots, leaving those who are exposed to them unaware of their health risks and in some cases misleading regulators about their existence” (Carlson, 2018, p. 1042). Relying on the CAA as it currently exists is not only ineffective but poses risk of causing environmental harm and perpetuating already existing injustices. Still there are solutions that exist outside of the CAA, and I hope that the work in this thesis stands as a framework for filling in the Clean Air Act’s current blind spots.

Ultimately, the path forward for the Duwamish River Valley and communities like it will likely not be an easy one. The CAA has been the dominant guiding policy in air pollution for decades now, with little indication of change coming soon. Despite the continuous rising tide of criticism for the CAA (GAO, 2020; Flatt, 2015; Walker & Storper 1978) and the EPA’s overall handling of the national air monitoring system, there has been little done in terms of substantial change. While lawsuits such as that pursued by the California Attorney General may be a step in the right direction towards creating change, air quality cannot be adequately monitored under the current system. Tighter NAAQS are not enough. Gonzalez’s criticism of the CAA concluded that “Without a CAA-mandated regulatory response, states will continue to take inefficient and ineffective baby steps toward acknowledging and eliminating substantial disparities in air quality at the local level” (Gonzalez, 2021, p. 149). Here, Gonzalez is speaking not to the need for tighter standards, but rather a new set of regulations creating systems that directly address hot spot pollution. Moss studies such as this are a critical step in demanding action by helping identify where hot spots exist.

There are far too many communities that are either receiving inaccurate or incomplete data, or in some cases, lack any sort of local monitoring at all. Time and time again, minority and
low-income communities are forced to bear the overwhelming weight of environmental injustices. Though one study of the moss in the DRV cannot undo decades of industrial pollution and hazardous waste, the community moss model offers an alternative to the Clean Air Act’s outdated, expensive, and ineffective model of air monitoring. Through moss studies such as this, communities are able to take back some control over their air quality, health, and safety.

    Thank you again to the members of the Duwamish River Community Coalition for their incredible support and collaboration throughout this process. This thesis would not have been possible without their support. The youth who helped collect and sort samples were an invaluable part of this process. Their hard work and willingness to become involved in the issues in their own neighborhood is what made this entire process possible. But beyond that, the Duwamish River Valley community as a whole has been incredibly helpful in guiding and supporting this project, particularly those collaborators at the Duwamish River Community Coalition. The future of the DRV air quality monitoring must be one that involves the community directly. This should be the case with any other community looking to follow a similar path of moss studies to evaluate pollution. Without meaningful involvement from communities, it is only a matter of time before more issues of environmental injustice begin to compound. It is only through meaningful collaboration and innovative approaches such as moss studies that we can fight together for breath of fresh air.
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