Filling in the Gaps: Using Consumer Products to Replace Missing Pollution Data

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Abstract

[abstract here]

1 Introduction

A critical input to good air quality regulation is good air quality measurement. Specifically, the efficiency of current pollution regulation hinges on our ability to accurately monitor air quality across the country. In the United States, air quality is assessed by the government using a network of monitors that measure levels of ambient air pollution to a high degree of accuracy. The Environmental Protection Agency (EPA) requires these monitors to measure average daily air quality at specific frequencies to ensure enough data is collected for effective regulation.[1] During the days that are required to be measured, the goal is to accurately measure the daily average pollution concentration at the site of the monitor. Statistics of these daily averages, called *design values*, are then used to decide if a region is in or out of compliance with the National Ambient Air Quality Standards (NAAQS).

Though these air quality monitoring stations are regulated by the EPA, they are managed by local and state officials who control when the monitors are on or off. For added flexibility, the EPA allows for some portion of air quality readings to be missing when calculating the design values that determine a region's compliance with the NAAQS. For instance, when

[1]The three main measurement frequencies require measuring daily average air quality every 1, 3 or 6 days.

measuring particulate matter in the air (one of the most common types of pollution), the EPA allows more than 25% of measurements to be missing or omitted (EPA, 2017).[2] In effect, this flexibility means that local managers of monitoring stations can choose up to 25% of readings to omit – readings that would otherwise be used to determine of compliance. Though the measurements of air quality at the site of the monitor are fairly accurate when the monitor is on, omitting some measurements (by turning the monitor off) can bias the daily average and compliance statistics calculated from reported measurements. Additionally, if a region is out of compliance with the standards, the region or state can potentially face large penalties and forced adoption of expensive abatement technology.

The combination of large penalties and the discretion local officials have to drop measurements that could negatively impact compliance status leads to misaligned incentives between federal regulators and local officials in charge of monitoring air quality, potentially leading to biased air quality statistics. Indeed, previous research suggests that there is mismeasurement of air quality statistics occurring; Zou (2021), Mu et al. (2021), Grainger et al. (2019) and Grainger and Schreiber (2019) provide evidence of strategic behavior in pollution measurement on behalf of local pollution regulators. This paper focuses the size of mismeasurement occurring and the effects this mismeasurement has on determining compliance.

Specifically, I explore the question: is there a bias in reported air quality data and how might this bias affect NAAQS compliance? To explore these issues, I utilize a new dataset of air quality measurements collected from consumer products (PurpleAir sensors). These data help provide an independent groundtruth comparison to air quality reported to the EPA. The most promising new data coming from these consumer products are PM2.5 measurements – the concentration of particles in air that are 2.5 micrometers and below. Specifically, I combine PM2.5 measurements from multiple PurpleAir sensors that are near to federally-

[2] Design values are used to decide compliance with NAAQS and are statistics of daily averages. In calculating daily averages, the daily average is valid if at least 75% of the hourly readings (18 of 24 hours) are reported and valid. In calculating the design values, the design value is valid if at least 75% of daily averages in each year are reported and valid. Combined, the minimum reporting standard is actually 56-57% of all required hourly PM2.5 readings. This is slightly different for each site depending on their reporting frequency (every 1, 3, or 6 days).

regulated monitoring stations to estimate the PM2.5 value at the monitoring station; I use inverse distance weighting to create a weighted average of PurpleAir measurements.[3] This allows me to construct predicted values of PM2.5 at the station during times when the station's readings would be used to calculated NAAQS compliance but when the station was shut down. I first examine how these predicted missing PM2.5 values compare to the reported values – if the missing data is missing at random, I would expect the data to be similar in distribution. Then I use the predicted values from PurpleAir sensors to fill in the gaps in the NAAQS monitor's reported data and use this reconstructed dataset to generate counterfactual NAAQS compliance statistics.

The NAAQS compliance statistics for PM2.5, called *design values*, are functions of the daily averages reported by air quality monitors. There are two primary design values for PM2.5: the "annual" design value is a three-year average of the daily averages; and "24-hour" design value is a three-year average of the annual 98^{th} percentile of daily averages.[4] Each quarter (3-month period), these two design values are calculated and compared to the NAAQS for PM2.5. If a monitor's design value is above the standard, then the monitor (and associated region) is determined to be in *non-attainment* (non-compliance) with the standard for that quarter. Using the reconstructed dataset of PM2.5 (PM2.5 estimates for all hours that would be reported from a given NAAQS monitor), I construct counterfactual estimates of the design values that determine if a region is in or out of attainment. I use these counterfactuals to determine which regions would have changed compliance status if they reported 100% of their PM2.5 measurements – I call these "flipped regions". I also examine how close these flipped regions were to the regulatory threshold and report a measure of the bias related to the station's missing PM2.5 readings.

Though I am examining the effect of pollution data that are missing from a monitor's

[3]Inverse distance weighting has drawbacks: it can apply very large weight to sensors very near to the NAAQS monitor and it does not take into account that some PurpleAir sensors will be better predictors for the NAAQS monitor. See Appendix section 6.2 for an alternative strategy that I plan to implement.

[4]these statistics are discussed more in the Data section. Specific formulas for these statistics are listed in the appendix.

record (data missing *in time*), there is also the issue of attempting to measure a region's ambient air quality using spatially sparse locations of monitors (you could consider this and issue of data missing *in space*). Previous literature has examined the sparse distribution of regulation-grade monitors and the resulting sensitivity of CAA air quality regulation. Grainger et al. (2019) and Grainger and Schreiber (2019) identify a principle-agent problem with the initial spatial placement of sparse pollution monitors; they find evidence that local regulators may be strategically locating their air quality monitors based on pollution, and possibly socioeconomic characteristics. To address the issue of sparse data and fill in the gaps, several authors have used satellite data products to provide finer resolution pollution data (Sullivan and Krupnick 2018, Fowlie et al. 2019). Moving to more time-based issues, Zou (2021) also uses satellite estimates to discuss the issue of strategic behavior in reaction to the timing of pollution monitoring. He provides evidence that some areas have significantly worse air quality on unmonitored days. In related work, Mu et al. (2021) show potential for strategic monitor shutdowns on days of expected high pollution, contributing to air quality data that is missing *in time*.

This paper is most similar to the analysis in Fowlie et al. (2019) where they use PM2.5 estimates generated from satellite data to examine counterfactual compliance status. However, they end their analysis noting that the satellite-based data commonly used in these applications has significant prediction error in some areas; this can cause result in incorrect conclusions about design values. This paper compliments their analysis and that of Mu et al., where I use a different form of ground-truth PM2.5 data to also address missing air quality data *in time*. [5] In contrast to Mu et al. however, I am examining pollution at times when it is missing in the data but required to be reported, whereas their work was on pollution at times that are not required to be reported. While satellite-based PM2.5 estimates have potential for large prediction errors, PurpleAir sensors can be fairly accurate measures of

[5] PurpleAir data, and other on-the-ground pollution sensors, also have the potential to examine issues of spatial distributions of monitor networks – work left for future research.

their local air quality[6] and can be averaged over multiple nearby sensors. PurpleAir data also have drawbacks however – the sensors are highly non-uniform in coverage across the US and are sensitive to specific placement by the consumer, perhaps leading to hyper-local estimates of air quality.

For these reasons, this analysis should be seen as a compliment to previous works. As consumer sensors become more widespread, we can augment reliable federal air quality measurements with a growing number of auxiliary data points to better understand the shape of mismeasurement in air quality. In this paper, I explore one way of leveraging these data to test for issues with biased reporting of air quality. After predicting missing observations using PurpleAir measurements, I do not find any statistically significant flipping of NAAQS compliance status in the 15 California NAAQS monitors. However, for a monitor in Fresno, CA, I do find differences between design values calculated on reported NAAQS data and design values calculated on imputed data; these differences persist for five quarters in 2020 and 2021 and are statistically significant at more than the 95% level. The largest discrepancy for Fresno is in the 24-hour design values, where the difference is more than $2.5\mu g/m^3$ of PM2.5 on average between 2018 and 2021. Fresno has been out of compliance for some time, and these results mimic previous literature that suggests larger pollution measurement problems in nonattainment areas. There is also evidence from previous research that pollution in non-attainment areas has been decreasing at significantly faster rates since the introduction of the CAA (Currie et al., 2020). Due to the small sample size of this study, there is not much evidence of widespread biased pollution standards. However, with the framework now setup, it would be possible to expand this type of analysis to all NAAQS monitors in the United States and all PurpleAir monitors available.

Ultimately, a possible outcome of this line of research is estimating the possible gains to be made in changing reporting standards. Increasing reporting standards to decrease

[6] PurpleAir sensors have specifically been shown to be less accurate than regulation-grade monitors at high levels of PM2.5 concentration. However, the EPA has developed a correction technique that result in PurpleAir readings within 5% of co-located EPA monitors. This correction technique is used here and explained in more detail in the appendix.

allowable omitted observations may result in more non-attainment areas and further increases regulatory efficiency.

The remainder of this article is organized as follows. Section 2 briefly reviews the history of air quality standard in the US and some key details of current regulations. Section 3 then discusses the data used and section **??** describes the theoretical and empirical framework that will be applied to estimate the missing pollution and effects on reference levels for national standards. Section 5 reviews the results of the empirical study and concludes.

2 Background

Amid growing public concern about air quality and pollution, the United States Congress passed the Clean Air Act of 1963 (CAA). Later additions to the CAA, the Clean Air Amendments of 1970, granted the Environmental Protection Agency (EPA) the regulatory authority to create and enforce air quality standards in the US. One major way air quality is regulated is through the National Ambient Air Quality Standards (NAAQS), which set concentration thresholds for a list of different "criteria" pollutants (91st US Congress, 1970). The EPA has since been in charge of setting and updating the NAAQS and require states to submit plans to bring their air quality to within NAAQS limits. An important aspect of enforcing the NAAQS is measuring criteria pollutants across the US by requiring states to install pollution monitoring stations in areas of questionable air quality. Because these monitoring stations are used for potentially costly enforcement, the equipment within each station must abide by specific regulations and are relatively costly to install and run.

Over the last decade, commercially available scientific equipment in measuring various air pollutants has evolved. There is now relatively cheap[7] equipment available to measure

[7]e.g., a PurpleAir outdoor air quality sensor is about $250 to purchase with little upkeep from the end user, compared to roughly $100,000-200,000 to install EPA regulation-grade criteria pollutant monitors and trained staff to upkeep and record measurements. The cost alone is not a good comparison because the EPA monitors use different technology that is known to be more accurate across a wider range of pollution concentrations, have a better sense the sensor error, and measure more pollutants than the PurpleAir monitors. For the purposes of this analysis, PurpleAir monitors should be seen as a compliment to EPA monitors, not a

particulate matter (one of the criteria pollutants that regulated by the NAAQS). Specifically, the PurpleAir company produces devices that can measure particulate matter that has a diameter of less than 2.5 micrometers (designated as PM2.5).[8] PurpleAir is of particular interest because they have built an opt-out mechanism for end-users to allow their ambient air quality data to be stored in the cloud. They also provide multiple ways for researchers and the general public to use this crowd-sourced air quality data.

This paper is primarily concerned with the minimum reporting requirement. As with many federal regulations, there are many ways that states or emitters can cleverly navigate the rules to emit more than they are meant to according to the spirit of the regulation. One way of navigating the CAA regulations is through the choice of what data to report. The EPA currently requires a minimum threshold of air quality data to be reported – for PM 2.5, 75% of daily measurements need to be reported, and each day must have 75% of hours reported. That leaves many choices of which hours to turn the monitor off for cleaning, calibration, or other reasons. I wish to understand how these timing decisions are affecting the distribution of reported data – specifically how it might be affecting a statistic of that distribution: the design value.

3 Data

3.1 EPA Regulation-grade Monitors

There are currently 388 air quality monitoring stations around the US that are used for NAAQS determination for PM2.5; I will refer to these monitors as *NAAQS monitors.* There are more regulation-grade monitors that meet or approach the regulatory accuracy standards set by the EPA, but these 388 are the monitors that are officially used to calculate the design values that decide NAAQS attainment status. Of the 388 NAAQS monitors in the US, I limit

potential replacement.

[8] PurpleAir devices can measure a few other criteria pollutants (namely ozone and PM10) but the comparability of the PM2.5 measurements between PurpleAir and EPA monitors are currently better understood.

my preliminary analysis on the 15 monitors in California that take hourly readings every day. Future analysis will include the full set of NAAQS monitors, which include monitors that only report daily averages (as opposed to hourly averages) and monitors that only report every 2, 3, 6, or 12 days.

Design Values. PM2.5 *design values* are statistics of hourly PM2.5 concentrations reported by the NAAQS monitors. In reality, design value determination for a monitor begins by calculating the initial design value on the non-missing data and then includes a negotiation step between EPA and the local regulator to decide the final, publicly-reported design value. I could use final design values for each monitor that are listed in EPA reports. However, I am interested in directly comparing the design values calculated from only reported data to design values that include predictions of unreported data. Because I cannot replicate the final negotiation process, I replicate work done in (Fowlie et al., 2019) to create *pseudo design values* by calculating the statistic on the data and making comparisons based on this initial design value. There are two NAAQS design values for PM2.5 explained in Section 4.2: annual and 24-hour. These design value calculations only use valid daily and annual averages, where validity is determined based on the number of reported and non-excluded observations.

Excluded Readings. There are a number of events that create air quality measurements that cannot be used in NAAQS determination; wildfires or machine calibrations (for example) can cause hour- or day-long readings to be invalid for the purposes of NAAQS determination. These times, referred to as *exceptional events* (EE), are events that are "not expected to recur routinely at a given location, or that [are] possibly uncontrollable or unrealistic to control through the [NAAQS regulatory] process"(EPA, 1990). These events are identified in the NAAQS monitor data and removed from the analysis: hours that have been labeled as EE are removed from both the PurpleAir and NAAQS monitor data before calculating design values.[9] These are not considered "missing" or "unreported" data for the sake of

[9] See Appendix Section 6.4 Table 19 for a detailed list of reasons that observations are excluded from NAAQS determinations.

predicting missing values, however these are considered invalid observations in the design value calculation. Removing EE provides more realistic pseudo design value estimates.

3.2 PurpleAir Consumer Sensors

The last ten years have seen a growing interest in consumer-based air quality measurement. PurpleAir air quality sensors are designed to mainly measure PM2.5, but also measure other pollutants (PM10, ozone) and environmental factors (humidity, temperature).[10]. In my analysis, PurpleAir PM2.5 data plays a ground-truth role – it gives me an alternative source of PM2.5 measurements to rely on when the NAAQS monitor is shut off.

To examine how design values might be influenced by missing data, I predict missing PM2.5 hourly average concentrations from EPA NAAQS monitors using nearby PurpleAir PM2.5 sensors. For an initial analysis, I limit the sample to include PurpleAir sensors within 5 miles of each NAAQS monitor, or extending up to 25 miles to get 10 PurpleAir sensors minimum for each monitor.

This is a fairly new and rich dataset: there have been more than 16,000 public PurpleAir sensors brought online in the United States since 2015. When a consumer is setting up their sensor, they have the choice to make the sensor public or private. All sensors upload their PM2.5 readings to an online server, but only public sensors have data available for research use. The company asks consumers to make their data public if possible, attempting to contribute to more citizen science. Of the 16,000+ US sensors, there are 10,401 in California, Oregon, Nevada, and Arizona and I limit my sample to the 592 unique PurpleAir sensors within 5 miles of 15 NAAQS-primary monitors.

Correction of PurpleAir Readings. PurpleAir sensors are known to have worse readings at higher levels of pollution. I modify PurpleAir PM2.5 values using the EPA's correction equation for PurpleAir sensors. The calibrated this equation by studying co-

[10]See Appendix section 6.5 for pictures of both a NAAQS monitoring station and a typical PurpleAir outdoor pollution sensor

located PurpleAir and NAAQS monitors.

$$\widetilde{PA}_{j,t} = \begin{cases} 0.52 * PA_{j,t} - 0.086 * H_{j,t} + 5.75, & \text{if } PA_{j,t} \leq 343\mu\text{g/m}^3 \\ 0.46 * PA_{j,t} + 0.(3.93e-4)PA_{j,t}^2 + 2.97, & \text{otherwise} \end{cases}$$

where $PA_{j,t}$ is the ambient PM2.5 measured by PurpleAir sensor j at time t and $H_{j,t}$ is the relative humidity (between 0 and 1) also measured by the PurpleAir device. This correction helps reduce concerns about heteroskedasticity due to larger errors in PurpleAir readings at high levels of PM2.5. Future work involves a more complex predictive model.

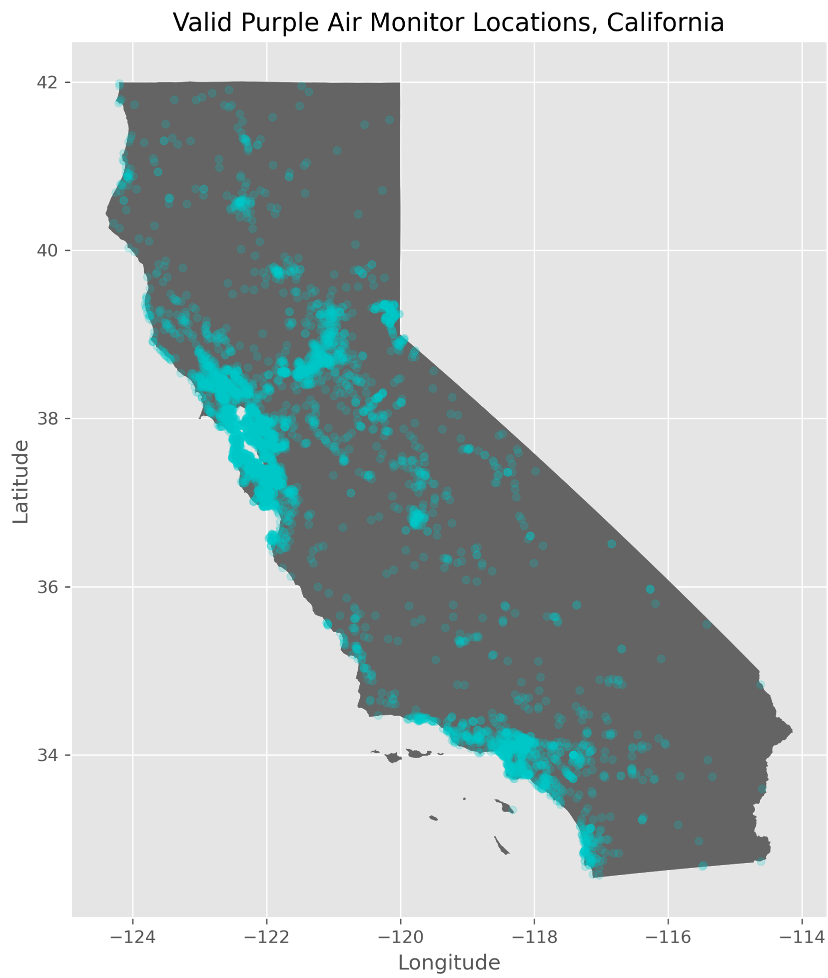


Figure 1: Map of PurpleAir sensors offering public, outdoor PM2.5 measurements. These are sensors that have offered any data in the past, so many are now inactive. The historical data is used in this analysis.

PurpleAir and a NAAQS Monitor. As an example, figure 2 depicts the high number of PurpleAir sensors in the vacinity of one of Los Angeles's NAAQS monitors. I select the PurpleAir sensors in pink, those within 5 miles of the monitor.

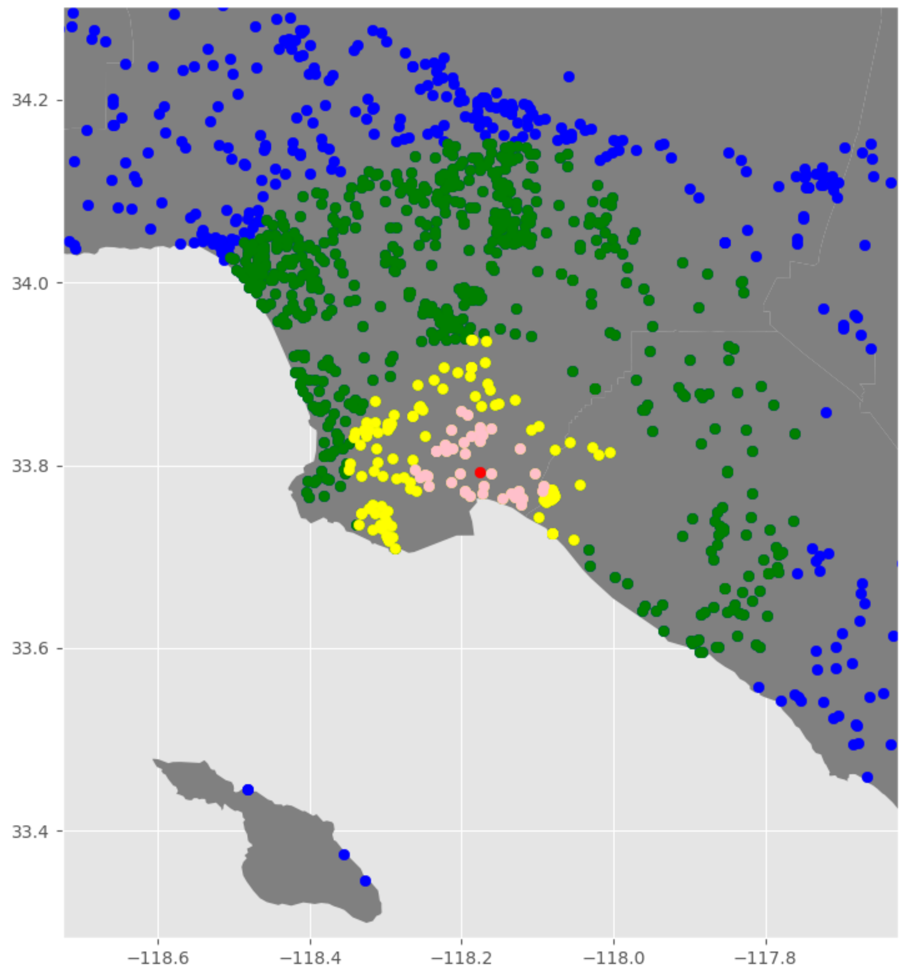


Figure 2: Map of an EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii. This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers).

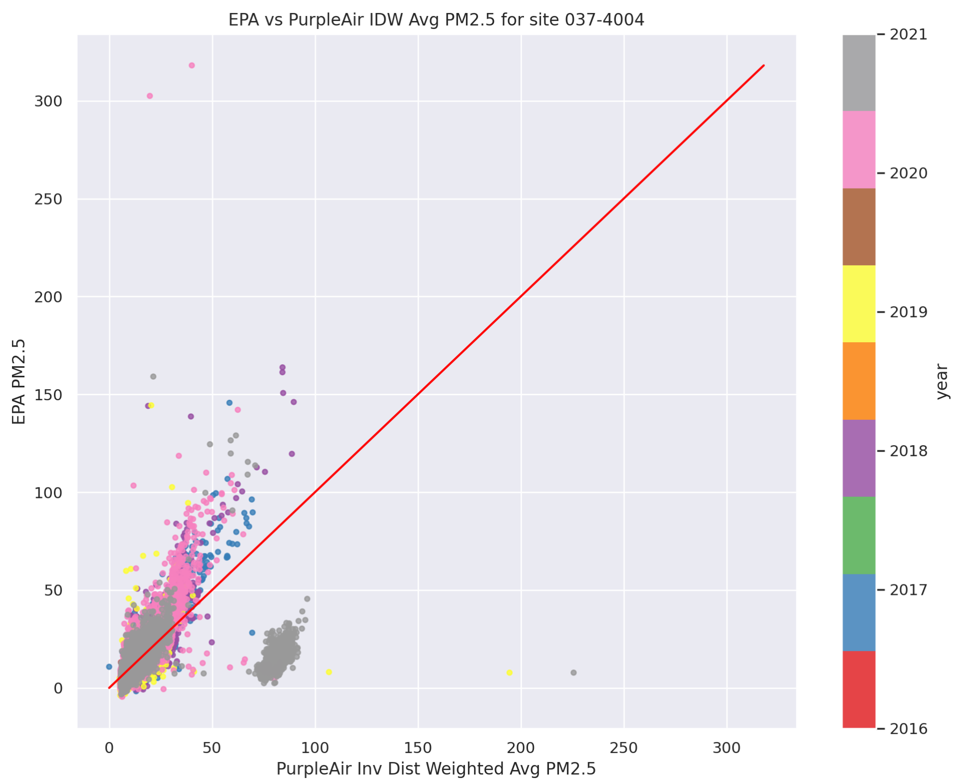


Figure 3: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. For this site, we can see the PurpleAir average is skewed to the right for readings from 2021. This is likely from a PurpleAir sensor coming online that was placed near a source of localized pollution that is not being picked up by the NAAQS-primary monitor.

3.3 Estimating Regulation-grade Readings with PurpleAir Sensors

I use inverse-distance weighting (IDW) with a power of 1 on the denominator. In their discussion of IDW in ambient pollution estimation, de Mesnard (2013) derives that a power between 1 and 3 is appropriate for diffuse particle distributions. I use a power of 1 here because I find evidence that some PurpleAir sensors that are very close to the NAAQS monitor are not very good predictors of the monitor's PM2.5 levels. These PurpleAir sensors seem to still have reliable estimates[11], and anecdotally seem to have very high PM2.5 readings when they disagree with the NAAQS monitor. This suggests they are measuring localized pollution that is out of the range of the NAAQS monitor (these sensors could be located next to a highway, for example).

I plan to fix this issue with a future implementation of a better prediction model[12]. In this iteration, I have implemented the sub-optimal IDW average to avoid excluding entire PurpleAir sensors and removing potentially useful sensor data.

4 Theoretical & Empirical Framework

4.1 Estimating PM2.5 at the NAAQS Monitor with PurpleAir Sensors

To examine the difference between reported pollution and that which is missing from the NAAQS monitors' dataset, I need some measure of ambient PM2.5 levels around the monitor. A good place to start is inverse distance weighting (IDW) to create a weighted average of PurpleAir sensors that can tell us about the PM2.5 levels near the NAAQS monitor.[13] To help make the estimation process concrete, I will use a monitor in Los Angeles, CA as an example (see Fig. 4 for a visual representation).

Consider an EPA NAAQS monitor that measures PM2.5 concentration EPA_T at time t. Let $PA_{j,t}$ be PM2.5 concentration as measured by PurpleAir sensor j at time t at a distance d_j from the NAAQS monitor. Assume that there are J_t active PurpleAir sensors in the vicinity of the NAAQS monitor at some time t, each with their own PM measurements and

[11] Each PurpleAir sensor has two internal sensors that measure PM2.5. Reliability of the PurpleAir sensors is determined by the agreement of the two sensors' hourly averages.

[12] See Appendix section 6.2

[13] This is not a good place to end, however. IDW produces fairly poor estimates of PM2.5 at the location of the NAAQS monitor (before OLS). I plan to implement a more rich prediction model using wind speed and direction – see the Appendix section 6.2 for model and data notes on this method. Ultimately, both satellite and PurpleAir data could be combined with NAAQS monitor data to provide a more accurate depiction of pollution in the US.

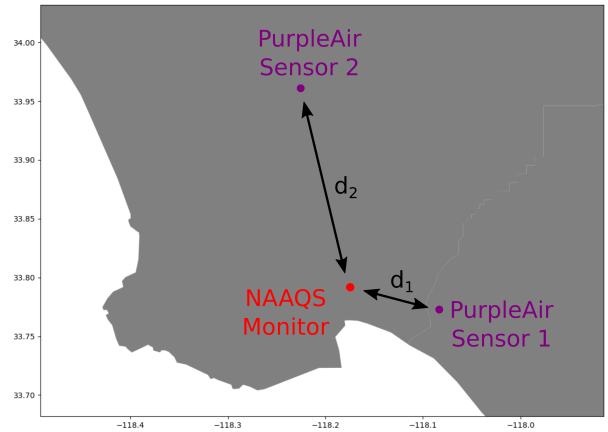


Figure 4: Example distances of two selected PurpleAir sensors near a NAAQS monitor in Los Angeles, CA.

distance. Then the Inverse-Distance Weighted average PurpleAir PM reading $PA_{j,t}^{IDW}$ is

$$PA_t^{IDW} = \sum_{j=1}^{J_t} \frac{\frac{1}{d_j} \cdot PA_{j,t}}{\sum_{j}^{J_t} \frac{1}{d_j}} = \sum_{j=1}^{J^t} w_{j,t} \cdot PA_{j,t} \tag{1}$$

Note here that I am explicitly using the exponent of one on the distance to balance the desire to have closer sensors provide more weight but avoid having extraordinarily large weights on sensors that are relatively close to the monitor. Also note that the number of PurpleAir sensors J_t changes over time as sensors come online and exit. This means the weights of the weighted average need to be calculated separately for each period. This IDW average PurpleAir measurement provides me with a measure of ambient PM2.5 variation in the vicinity of the NAAQS monitor at all the possible times there exists at least one PurpleAir monitor in the area. This helps provide good coverage and make implementing OLS in the next step easier.

OLS Prediction. Even if the PurpleAir sensors are highly accurate at measuring PM2.5 concentrations at their location, they may still biased as measures of PM2.5 near the NAAQS monitor. For example, someone might put up a PurpleAir sensor on a telephone pole right next to a highway, which might have high average PM compared to where the NAAQS monitor is placed. To help ensure an unbiased approximation of the missing monitor measurements *at the location of the NAAQS monitor*, I use OLS to regress the NAAQS monitor data on the weighted average PurpleAir data.

$$EPA_t = \beta_0 + \beta_1 PA_t^{IDW} + \varepsilon_t \tag{2}$$

I then predict missing NAAQS monitor data (out of sample) and combine the predicted PM estimate with the reported readings. Formally, suppose $\mathcal{M}$ is the set of **missing** times that we do not have a PM record from the NAAQS monitor (i.e., EPA_t does not exist for $t \in \mathcal{M}$). Let $\mathcal{N}$ be the **non-missing** (reported) times for the NAAQS monitor ($EPA_t \in \mathbb{R}\ \forall t \in \mathcal{N}$). For simplicity, assume that some PurpleAir data are available at all times ($PA_t^{IDW} \in \mathbb{R}_+\ \forall t \in \mathcal{M} \bigcup \mathcal{N}$). Using the PurpleAir data during the missing times, I predict the missing NAAQS data:

$$\widehat{EPA}_t = \hat{\beta}_0 + \hat{\beta}_1 PA_t^{IDW} \quad \forall t \in \mathcal{M} \tag{3}$$

I also estimate the 95% lower and upper bound on each predicted value; $\widehat{EPA}_t^L$ and $\widehat{EPA}_t^U$ to later using in lower and upper bounds on the design value.

4.2 Estimating Design Values

The NAAQS specify two primary statistics to determine if an area is in or out of attainment. These two statistics are referred to as the Annual and 24-hour Design Values. The annual design value is a 3-year average of annual averages of daily average PM2.5 levels. The 24-hour design value is a 3-year average of the annual 98th percentile of daily averages. There are also considerations about the proportion of allowed missing recordings (75%). See Appendix Section 6.3 for details on constructing these design values.

I first construct design values using the reported NAAQS monitor data. In the style of Fowlie et al. (2019), I will call these annual and 24-hour *pseudo design values*; DV_A and

DV_H. I do not use the reported design values because there is a more complex negotiation that happens between the EPA and state regulators that can change some of the numbers. In order to compare design values between reported and reported + imputed datasets, I must calculate them on the actual reported PM2.5 readings from the NAAQS monitor.

I then create predicted NAAQS PM values using PurpleAir data as described in the previous section. I replace all missing NAAQS monitor values possible with the predicted values, leaving the original valid NAAQS readings. With this new imputed dataset, I calculate the new imputed design values: $\widetilde{\mathrm{DV}}_A$ and $\widetilde{\mathrm{DV}}_H$. Subtracting the original design value from the imputed design value gives an estimate of design value bias caused by missing data.

$$\mathrm{bias}^{miss}(\mathrm{DV}_A) \approx \widetilde{\mathrm{DV}}_A - \mathrm{DV}_A \tag{4}$$

$$\mathrm{bias}^{miss}(\mathrm{DV}_H) \approx \widetilde{\mathrm{DV}}_H - \mathrm{DV}_H \tag{5}$$

If this quantity is positive, then there is support that there is under-reporting of pollution via allowed missing data. To gain an understanding of significance of the results, I also propagate the upper and lower bounds of the predicted observations through the design value calculation (similar to Fowlie et al. (2019), but they were estimating out of sample prediction errors). This provides a 95% confidence interval – upper and lower bounds on the imputed design values: $\widetilde{\mathrm{DV}}_A^{upper}$, $\widetilde{\mathrm{DV}}_A^{lower}$, $\widetilde{\mathrm{DV}}_H^{upper}$, and $\widetilde{\mathrm{DV}}_H^{lower}$.

NAAQS. The standards set out in the National Ambient Air Quality Standards give specific thresholds to compare the design values to. Above the thresholds are considered nonattainment. The primary standard for the annual design value is 12 μg/m^3, and has a secondary standard of 12 μg/m^3. The 24-hour standard is 35 μg/m^3.

Exceptional Events. As mentioned in section 3, there are many events for which the EPA allows local regulators to exclude their readings from design value calculations. These readings were removed from the dataset before any design value calculations and do not get imputed.

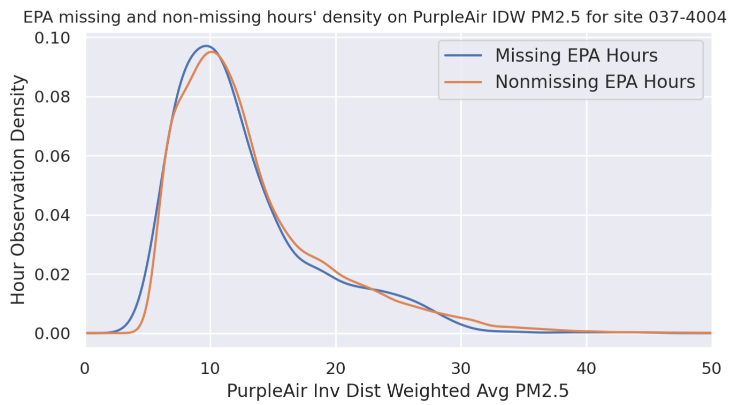
5 Results and Discussion

I conducted 15 design value tests on 15 different NAAQS monitors. To create the predicted design value for each NAAQS monitor, I regressed the NAAQS monitor PM2.5 readings on the weighted average PurpleAir readings. An example of this regression is below for one of the Los Angeles monitors. I ran regions both with an without a constant, but because I wanted the prediction errors to have mean zero, I chose to use model (2) in the creation of the design value. Note that the R^2 value in model (1) is much higher, however R^2 values between regressions with constant and those without are no comparable due to the difference in denominators.

Table 1: 037-4004 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		6.924***
		(0.076)
PurpleAir IDW Average	0.741***	0.444***
	(0.003)	(0.004)
Preferred	No	Yes
Observations	36,813	36,813
R^2	0.658	0.240
Adjusted R^2	0.658	0.240
Residual Std. Error	9.870	8.920
F Statistic	70924.412***	11642.169***
Note:		*p<0.1; **p<0.05; ***p<0.01

The number of observations here are the number of hours between 2016 and 2021 where neither the NAAQS monitor or the weighted average PurpleAir readings were missing. The slope in both models is less than one, indicating that PurpleAir tends to measure higher PM2.5 concentrations. This could be a selection issue – consumers who choose to buy a



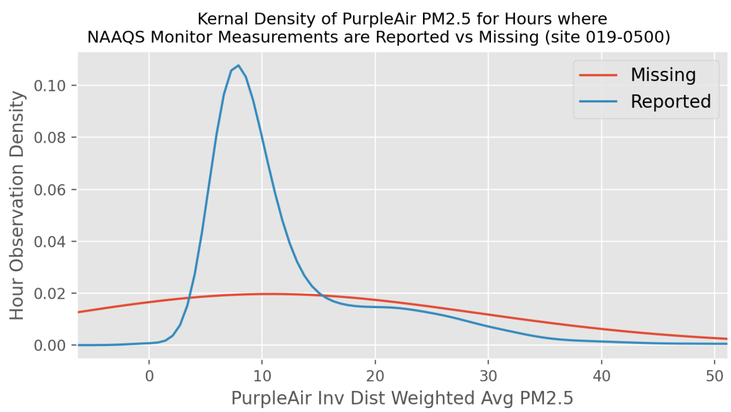


Figure 5: Comparison of estimated kernel densities of PM2.5 concentration for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. The top image is for a monitor at a site in LA, and the bottom is at a site in Fresno, CA.

PurpleAir monitor and place it outside their house are probably concerned about pollution – or a measurement difference between the types of devices.

For all sites, I generated kernel density plots like those in Fig. 5. Only one of the 15 sites I tested had noticeable differences in the PM2.5 distributions for missing and reported hours (see the appendix for all sites' plots). However, the design values are the policy-relevant statistic of those distributions. Looking at the top and bottom figures below however, we can guess that the means and 98th percentile might be similar in the top case, and could plausibly be different in the bottom case.

Table 2 reports the difference between the pseudo design value (calculated using the

Table 2: Design Value Comparison for Fresno, CA. (98% CI Bounds)

Year-Quarter	Annual DV Difference	Upper Bound	Lower Bound	Hour DV Difference	Upper Bound	Lower Bound
2018-4	Invalid DV			Invalid DV		
2019-1	-0.005	0.133	-0.143	0.000	0.252	0.000
2019-2	-0.003	0.141	-0.147	0.000	0.252	0.000
2019-3	0.015	0.170	-0.139	0.058	2.202	0.000
2019-4	0.002	0.190	-0.185	0.000	1.460	-0.024
2020-1	-0.012	0.182	-0.207	0.000	0.335	0.000
2020-2	-0.010	0.191	-0.211	0.000	0.376	0.000
2020-3	0.679	0.954	0.403	8.718	11.704	8.556
2020-4	0.647	1.006	0.288	5.979	8.281	5.851
2021-1	0.564	1.036	0.091	3.007	4.184	2.903
2021-2	0.533	1.024	0.042	3.007	4.225	2.903
2021-3	0.630	1.129	0.132	7.607	10.557	7.444

reported data) and the imputed design value – what I believe is an estimate on the design value bias due to low reporting standards. We can see the first row is invalid. This is common in the full results in the Appendix. This occurs because one of the design values have too many invalid days in the quarter (or the 11 quarters before it) the completeness criteria are violated. Examining the Annual design value difference column, the numbers do not seem striking though the lower half do seem to be statistically significant. However, these are not materially significant – the EPA has rounding conventions (to the ones place) that would make zero effectively within the lower bound since a design value falling below 0.5 would be rounded to 0.

These unremarkable results for the annual design value bias are fairly representative of the batch of 15 sites. When we look at the hour design value results, we can see in 2020 and 2021, there were fairly large and significant differences between the design values. This indicates that having more restrictive data collection standards could have increased Fresno's design value significantly in these quarters. Because OLS was used to impute the missing values, we would expect the hourly imputed values to be unbiased on average. Since we are taking 3-year averages, it seems plausible to believe most bias in the imputation method would average out. These combined with the lower bounds being well above zero suggest there was indeed under-reporting of pollution in Fresno. I cannot say whether or not that it happened intentionally or by mere chance of turning off the monitor at times that would likely have recorded higher pollution.

Is this meaningful for Fresno though? Fresno has had a nonattainment status for many years and is listed on several lists within this literature as having notable pollution measurement issues. So though Fresno's recorded design value would have been higher, they were already well over the 24-hour design threshold of 35 $\mu g/m^3$, having pseudo design values in the 50s and 60s in 2020 and 2021.

This is also just one of 15 cases, where the other 14 did not show interesting results. So is this just p-hacking to find the case study that is, by chance, abnormal? In regulation of air pollution, one might be concerned with individual actors or regions trying to get around the regulations. Since the Clean Air Act and the NAAQS are designed to ensure that all American residents can share in a minimum standard, it seems relevant to me to be able to diagnose mismeasurement.

This work is (hopefully) just the beginning of a line of research regarding the distribution of pollution and pollution policies in the US. There is a to-do list in the Appendix.

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6 Appendix

6.1 Research Project To-do's

Future Work

- I have only tested 15 of 388 possible sites. Now that I have written the bulk of the code the manage the data, most of the future work lies in acquiring the rest of the data for the NAAQS monitors and PurpleAir monitors.

- I am in the process of negotiating a data usage agreement with PurpleAir staff to get the entire historical dataset of all US sensors. This is the main bottleneck.

- I have written code to download any arbitrary NAAQS sensor data between two dates. However, some of the NAAQS monitors report on a less frequent basis than hourly, so the analysis code will need to be generalized for other reporting frequencies.

- I have written code to download wind velocity data, but parsing the files to get wind velocity at a particular location and time requires more work. This will be used in my predictive model for missing PM2.5 data at the NAAQS monitor.

6.2 Improving Prediction of PM2.5 at the NAAQS Monitor Location

A more realistic model of predicting pollution at the EPA monitor could be used. Using wind direction (and possibly wind speed), we can intuitively put more weight on PurpleAir sensors that are North of the EPA monitor when the wind is blowing South. This model allows for mroe flexibility in dropping some sensors that may be measuring hyper-local pollution and are not good predictors of the EPA monitor's PM2.5 readings.

$$EPA_{i,t} = \gamma_{i,0} + \sum_{j \in J_i} \sum_{k=1}^{7} \gamma_{i,j,k} PA_{j,t} \cdot Winddir_{i,t,k} + u_{i,t}$$

- Each EPA monitor i has it's own set of weights for the PA sensors around it.
- Analysis is done at the quarter level; suppressing quarter subscript.
- t is a unique hour within a given quarter.
- EPA monitor i at time t reads PM2.5 pollution $EPA_{i,t}$.
- For each EPA monitor i, there are J_i Purple Air monitors within a 5-mile radius.
- Purple Air monitor $j \in J_i$ at time t reads PM2.5 pollution $PA_{j,t}$.
- $Winddir_{i,t,k}$ is a wind direction indicator; 1 if the prevailing wind near station i at time t is in the k^{th} bucket (of 8 buckets).
- I will also estimate a version with wind speed interacted in the sum. This could allow for sensors further away to have more predictive power when the winds are strong.
- This regression could be run as a LASSO first to determine which of the interactions for each PurpleAir sensor have the most predictive power.

6.3 Design Values

Notes about design values:

- Valid days: a day that has 18 or more valid hours in it.
- Valid quarters: a 3-month period that has at least 67. 68, or 69 valid days in it.
- Valid 3-year period: a 12-quarter period that has 12 valid quarters in it.
- A design value is only valid if its 3-year period is valid.
- All averages below assume there might be some data missing.
- Design values are based on quarters, so each quarter has a rolling average over the last 3 years before.

To construct the annual design value for a given quarter:

- Construct an average for every day.
- Construct an annual average of daily averages for every previous 12-month period before this quarter.
- Construct the 3-year average of those annual averages. Because some years have a different number of real or valid days in them, you cannot take a simple 3-year average of all available days or hours.

To construct the 24-hour design value:

- Construct an average for every day.
- Construct a 98th percentile of all daily averages in the 4-quarter period ending in this quarter. To avoid ambiguous design value construction, the EPA provides a lookup table for which n^{th} maximum daily value to take when constructing the 98th percentile.
- Take a 3-year average of the 98th percentiles.

6.4 Tables

Table 3: Design Value differences and bounds: NAAQS Monitor DV subtracted from the imputed DV. The imputed DV was created by imputing the missing NAAQS Monitor observations with OLS predictions from a regression of the NAAQS PM2.5 values on the weighted average of nearby PurpleAir sensors' PM2.5 values. Positive values represent an upward bias in the missing PM2.5 measurements. The lower (upper) bound of the DV difference is calculated by finding the lower (upper) bound of the imputed DV and holding the "pure" DV constant. The imputed DV lower bound is found by imputing missing values with the 95% lower bound of each predicted observation (the prediction confidence interval), then re-computing the imputed DV with the lower bound data.

County	Site	Year-Quarter	County In Attainment ?	In Attainment based on Psedo DV?	Annual DV Difference	Lower Bound	Upper Bound	Hour DV Difference	Lower Bound	Upper Bound
37	4004	2018-4	N	N	-0.016	0.340	-0.373	-0.885	-0.885	-0.885
37	4004	2019-1	N	N	-0.023	0.337	-0.383	-0.617	-0.114	-0.617
37	4004	2019-2	N	N	-0.031	0.336	-0.397	-0.617	-0.617	-0.617
37	4004	2019-3	N	N	-0.016	0.392	-0.424	-0.617	1.570	-0.617
37	4004	2019-4	N	N	-0.010	0.404	-0.424	-0.885	-0.792	-0.885
37	4004	2020-1	N	N	-0.021	0.403	-0.445	-0.617	0.023	-0.617
37	4004	2020-2	N	N	-0.040	0.573	-0.653	-0.754	-0.356	-0.754
37	4004	2020-3	N	N	-0.065	0.480	-0.609	-0.617	0.113	-0.617

37	4004	2020-4	N	N	-0.065	0.461	-0.591	-0.336	-0.243	-0.336
37	4004	2021-1	N	N	-0.065	0.406	-0.536	-0.083	0.557	-0.083
37	4004	2021-2	N	N	-0.046	0.387	-0.478	-0.138	0.260	-0.138
37	4004	2021-3	N	N	-0.050	0.385	-0.485	0.000	0.730	0.000
31	1004	2018-4	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2019-1	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2019-2	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2019-3	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2019-4	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2020-1	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2020-2	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2020-3	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2020-4	N	–	Invalid DV	–	–	Invalid DV	–	–
31	1004	2021-1	N	–	Invalid DV	–	–	Invalid DV	–	–
57	5	2020-3	Y	–	Invalid DV	–	–	Invalid DV	–	–

57	5	2020-4	Y	–	Invalid DV	–	–	Invalid DV	–	–
57	5	2021-1	Y	–	Invalid DV	–	–	Invalid DV	–	–
57	5	2021-2	Y	–	Invalid DV	–	–	Invalid DV	–	–
57	5	2021-3	Y	–	Invalid DV	–	–	Invalid DV	–	–
1	13	2019-2	Y	N	-0.044	0.320	-0.408	-0.758	0.263	-0.758
1	13	2019-3	Y	N	-0.018	0.446	-0.482	-1.228	-0.684	-1.506
1	13	2019-4	Y	N	-0.008	0.569	-0.586	-0.049	3.469	-0.049
1	13	2020-1	Y	N	-0.018	0.668	-0.703	-0.842	4.791	-0.842
1	13	2020-2	Y	N	-0.010	0.687	-0.708	-0.929	4.791	-1.147
1	13	2020-3	Y	N	-0.044	0.705	-0.793	-1.228	-0.337	-1.506
1	13	2020-4	Y	N	-0.028	0.721	-0.777	0.000	3.740	0.000
1	13	2021-1	Y	N	0.007	0.817	-0.803	-0.083	6.474	-0.083
1	13	2021-2	Y	N	0.012	0.785	-0.760	-0.171	6.474	-0.389
19	500	2018-4	N	–	Invalid DV			Invalid DV		
19	500	2019-1	N	Y	-0.005	0.133	-0.143	0.000	0.252	0.000

19	500	2019-2	N	Y	-0.003	0.141	-0.147	0.000	0.252	0.000
19	500	2019-3	N	Y	0.015	0.170	-0.139	0.058	2.202	0.000
19	500	2019-4	N	Y	0.002	0.190	-0.185	0.000	1.460	-0.024
19	500	2020-1	N	Y	-0.012	0.182	-0.207	0.000	0.335	0.000
19	500	2020-2	N	Y	-0.010	0.191	-0.211	0.000	0.376	0.000
19	500	2020-3	N	N	0.679	0.954	0.403	8.718	11.704	8.556
19	500	2020-4	N	N	0.647	1.006	0.288	5.979	8.281	5.851
19	500	2021-1	N	N	0.564	1.036	0.091	3.007	4.184	2.903
19	500	2021-2	N	N	0.533	1.024	0.042	3.007	4.225	2.903
19	500	2021-3	N	N	0.630	1.129	0.132	7.607	10.557	7.444
19	5001	2018-4	N	N	0.031	0.733	-0.671	-1.703	-1.703	-1.703
19	5001	2019-1	N	N	0.060	1.095	-0.975	-1.702	0.118	-1.702
19	5001	2019-2	N	–	Invalid DV	–	–	Invalid DV	–	–
19	5001	2019-3	N	–	Invalid DV	–	–	Invalid DV	–	–
19	5001	2019-4	N	–	Invalid DV	–	–	Invalid DV	–	–

19	5001	2020-1	N	–	Invalid DV	–	–	Invalid DV	–	–
19	5001	2020-2	N	–	Invalid DV	–	–	Invalid DV	–	–
19	5001	2020-3	N	–	Invalid DV	–	–	Invalid DV	–	–
19	5001	2020-4	N	–	Invalid DV	–	–	Invalid DV	–	–
19	5001	2021-1	N	–	Invalid DV	–	–	Invalid DV	–	–
27	2	2018-4	Y	Y	-0.001	0.058	-0.060	0.000	0.000	0.000
27	2	2019-1	Y	Y	0.002	0.206	-0.203	-0.299	-0.299	-0.299
27	2	2019-2	Y	Y	0.005	0.211	-0.202	-0.061	-0.061	-0.061
27	2	2019-3	Y	Y	0.018	0.257	-0.220	-0.039	4.018	-0.039
27	2	2019-4	Y	Y	0.006	0.250	-0.239	0.000	3.794	0.000
27	2	2020-1	Y	Y	-0.006	0.346	-0.358	-0.299	2.637	-0.299
27	2	2020-2	Y	Y	-0.007	0.406	-0.420	-0.082	2.869	-0.082
27	2	2020-3	Y	Y	-0.009	0.420	-0.438	-0.039	4.018	-0.039
27	2	2020-4	Y	Y	0.021	0.531	-0.490	0.000	4.292	0.000
27	2	2021-1	Y	Y	0.017	0.595	-0.562	-0.299	3.134	-0.299

27	2	2021-2	Y	Y	0.001	0.695	-0.693	-0.082	3.367	-0.082
29	18	2020-3	N	–	Invalid DV	–	–	Invalid DV	–	–
29	18	2020-4	N	Y	0.002	0.047	-0.043	0.000	0.000	0.000
29	18	2021-1	N	Y	-0.008	0.174	-0.190	0.000	0.000	0.000
29	18	2021-2	N	Y	-0.006	0.318	-0.331	0.000	0.000	0.000
31	4	2019-4	N	N	0.000	0.000	0.000	0.000	0.000	0.000
31	4	2020-1	N	N	0.000	0.000	0.000	0.000	0.000	0.000
31	4	2020-2	N	N	0.000	0.000	0.000	0.000	0.000	0.000
31	4	2020-3	N	N	0.000	0.000	0.000	0.000	0.000	0.000
31	4	2020-4	N	N	-0.002	0.012	-0.015	0.000	0.000	0.000
31	4	2021-1	N	N	-0.057	0.035	-0.150	0.000	0.000	0.000
31	4	2021-2	N	N	-0.052	0.047	-0.150	-1.376	-1.376	-1.376
39	2010	2018-4	N	N	0.000	0.000	0.000	0.000	0.000	0.000
39	2010	2019-1	N	N	0.000	0.000	0.000	0.000	0.000	0.000
39	2010	2019-2	N	N	0.000	0.000	0.000	0.000	0.000	0.000

39	2010	2019-3	N	N	0.000	0.000	0.000	0.000	0.000	0.000
39	2010	2019-4	N	N	0.000	0.001	-0.002	0.000	0.000	0.000
39	2010	2020-1	N	N	0.001	0.009	-0.007	0.000	0.000	0.000
39	2010	2020-2	N	N	0.000	0.016	-0.015	0.000	0.000	0.000
39	2010	2020-3	N	N	-0.001	0.020	-0.021	0.000	0.000	0.000
39	2010	2020-4	N	N	-0.001	0.024	-0.025	0.000	0.000	0.000
39	2010	2021-1	N	N	-0.007	0.085	-0.098	0.000	0.000	0.000
39	2010	2021-2	N	N	-0.007	0.089	-0.103	0.000	0.000	0.000
59	7	2018-4	N	N	0.002	0.018	-0.014	0.000	0.000	0.000
59	7	2019-1	N	N	0.002	0.026	-0.022	0.000	0.000	0.000
59	7	2019-2	N	Y	0.002	0.031	-0.027	0.000	0.000	0.000
59	7	2019-3	N	Y	0.002	0.037	-0.033	0.000	0.000	0.000
59	7	2019-4	N	Y	0.002	0.041	-0.038	0.000	0.000	0.000
59	7	2020-1	N	Y	0.023	0.078	-0.031	0.000	0.492	-0.254
59	7	2020-2	N	Y	0.001	0.118	-0.117	0.000	0.492	-0.254

59	7	2020-3	N	Y	-0.003	0.121	-0.127	0.000	0.000	0.000
59	7	2020-4	N	Y	-0.011	0.120	-0.143	0.000	0.000	0.000
59	7	2021-1	N	Y	0.006	0.155	-0.143	0.000	0.492	-0.254
59	7	2021-2	N	Y	0.016	0.214	-0.183	0.000	0.492	-0.254
59	7	2021-3	N	Y	0.015	0.215	-0.186	0.000	0.771	0.000
67	5003	2020-1	Y	–	Invalid DV	–	–	Invalid DV	–	–
67	5003	2020-2	Y	Y	-0.002	0.202	-0.206	0.000	0.833	0.000
67	5003	2020-3	Y	N	-0.005	0.201	-0.210	0.000	0.000	0.000
67	5003	2020-4	Y	N	-0.003	0.204	-0.210	0.000	1.601	-0.029
67	5003	2021-1	Y	N	-0.011	0.199	-0.220	0.000	0.833	0.000
67	5003	2021-2	Y	N	-0.001	0.216	-0.219	0.000	0.833	0.000
77	2010	2018-4	N	N	0.005	0.039	-0.028	0.000	0.000	0.000
77	2010	2019-1	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2019-2	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2019-3	N	–	Invalid DV	–	–	Invalid DV	–	–

77	2010	2019-4	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2020-1	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2020-2	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2020-3	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2020-4	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2021-1	N	–	Invalid DV	–	–	Invalid DV	–	–
77	2010	2021-2	N	–	Invalid DV	–	–	Invalid DV	–	–
83	11	2020-2	Y	–	Invalid DV	–	–	Invalid DV	–	–
83	11	2020-3	Y	Y	0.020	0.423	-0.382	-1.361	-0.560	-1.361
83	11	2020-4	Y	Y	0.024	0.429	-0.380	-0.083	1.398	-0.083
83	11	2021-1	Y	Y	0.016	0.419	-0.388	-0.083	1.398	-0.083
83	11	2021-2	Y	Y	0.008	0.537	-0.522	-1.639	0.641	-1.639
83	11	2021-3	Y	Y	0.017	0.559	-0.526	-1.625	-0.052	-1.625
103	7	2018-4	Y	–	Invalid DV	–	–	Invalid DV	–	–
103	7	2019-1	Y	Y	-0.007	0.146	-0.160	-0.675	0.000	-1.208

103	7	2019-2	Y	Y	-0.005	0.155	-0.164	-0.675	0.000	-1.208
103	7	2019-3	Y	N	0.010	0.182	-0.162	0.000	2.597	-0.323
103	7	2019-4	Y	Y	0.024	0.325	-0.277	-0.675	1.855	-1.222
103	7	2020-1	Y	Y	0.023	0.528	-0.481	-0.716	3.444	-1.250
103	7	2020-2	Y	Y	0.026	0.594	-0.542	-0.716	3.444	-1.250
103	7	2020-3	Y	N	-0.062	0.618	-0.741	-0.972	1.625	-1.295
103	7	2020-4	Y	N	-0.043	0.652	-0.739	-1.647	0.883	-2.194
103	7	2021-1	Y	N	-0.065	1.058	-1.188	-1.689	2.472	-2.222
103	7	2021-2	Y	N	-0.052	1.199	-1.303	-1.689	2.472	-2.222

Table 4: Current NAAQS Nonattainment Counties

State	Area Name	EPA Designated Nonattainment Counties	FIPS	# of monitors in sample
CA	Imperial County, CA	Imperial, CA (p)	025	
	San Joaquin Valley Air Basin, CA	Fresno, CA	019	2
		Kern, CA (p)	029	1
		Kings, CA	031	2
		Madera, CA	039	1
		Merced, CA	047	
		San Joaquin, CA	077	1
		Stanislaus, CA	099	
		Tulare, CA	107	
	Los Angeles-South Coast Air Basin, CA	Los Angeles, CA (p)	037	1
		Orange, CA	059	1
		Riverside, CA (p)	065	
		San Bernardino, CA (p)	071	
	Plumas County, CA	Plumas, CA (p)	063	
ID	West Silver Valley, ID	Shoshone, ID (p)	079	
OH	Cleveland, OH	Cuyahoga, OH	035	
		Lorain, OH	093	
PA	Delaware County, PA	Delaware, PA	035	

	Lebanon County, PA	Lebanon, PA	075	
	Allegheny, PA	Allegheny, PA	005	

Table 5: 001-0013 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		6.766***
		(0.093)
PurpleAir IDW Average	0.338***	0.192***
	(0.002)	(0.003)
Preferred	No	Yes
Observations	34,619	34,619
R^2	0.399	0.111
Adjusted R^2	0.398	0.111
Residual Std. Error	13.364	12.454
F Statistic	22935.628***	4340.693***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 6: 019-0500 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-7.724***
		(0.081)
PurpleAir IDW Average	1.125***	1.401***
	(0.003)	(0.004)
Preferred	No	Yes
Observations	32,016	32,016
R^2	0.784	0.784
Adjusted R^2	0.784	0.784
Residual Std. Error	11.640	10.269
F Statistic	116065.720***	116450.963***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 7: 019-5001 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		13.919***
		(0.115)
PurpleAir IDW Average	0.177***	0.075***
	(0.002)	(0.002)
Preferred	No	Yes
Observations	26,838	26,838
R^2	0.171	0.047
Adjusted R^2	0.171	0.047
Residual Std. Error	21.444	17.244
F Statistic	5549.054***	1311.050***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 8: 027-0002 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-4.507***
		(0.081)
PurpleAir IDW Average	1.046***	1.329***
	(0.005)	(0.007)
Preferred	No	Yes
Observations	25,671	25,671
R^2	0.624	0.586
Adjusted R^2	0.624	0.586
Residual Std. Error	9.404	8.882
F Statistic	42589.056***	36294.550***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 9: 029-0018 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		10.655***
		(0.259)
PurpleAir IDW Average	0.042***	-0.020***
	(0.002)	(0.002)
Preferred	No	Yes
Observations	8,520	8,520
R^2	0.052	0.008
Adjusted R^2	0.052	0.008
Residual Std. Error	19.940	18.209
F Statistic	471.879***	72.168***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 10: 031-0004 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-2.227***
		(0.159)
PurpleAir IDW Average	1.109***	1.198***
	(0.005)	(0.008)
Preferred	No	Yes
Observations	9,132	9,132
R^2	0.861	0.719
Adjusted R^2	0.861	0.719
Residual Std. Error	9.036	8.941
F Statistic	56771.178***	23331.302***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 11: 031-1004 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-1.542***
		(0.196)
PurpleAir IDW Average	1.198***	1.255***
	(0.006)	(0.009)
Preferred	No	Yes
Observations	6,981	6,981
R^2	0.868	0.728
Adjusted R^2	0.868	0.728
Residual Std. Error	9.941	9.898
F Statistic	45870.404***	18650.990***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 12: 039-2010 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-8.235***
		(0.105)
PurpleAir IDW Average	1.075***	1.383***
	(0.004)	(0.005)
Preferred	No	Yes
Observations	15,227	15,227
R^2	0.843	0.831
Adjusted R^2	0.843	0.831
Residual Std. Error	9.642	8.137
F Statistic	81867.760***	75091.538***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 13: 057-0005 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		9.149***
		(0.146)
PurpleAir IDW Average	0.020***	0.005***
	(0.001)	(0.001)
Preferred	No	Yes
Observations	24,423	24,423
R^2	0.021	0.001
Adjusted R^2	0.021	0.001
Residual Std. Error	23.532	21.836
F Statistic	530.156***	35.924***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 14: 059-0007 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-3.169***
		(0.082)
PurpleAir IDW Average	0.992***	1.213***
	(0.003)	(0.006)
Preferred	No	Yes
Observations	29,577	29,577
R^2	0.781	0.545
Adjusted R^2	0.781	0.545
Residual Std. Error	6.705	6.542
F Statistic	105282.862***	35369.085***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 15: 067-5003 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-2.488***
		(0.078)
PurpleAir IDW Average	1.047***	1.205***
	(0.005)	(0.007)
Preferred	No	Yes
Observations	20,504	20,504
R^2	0.683	0.594
Adjusted R^2	0.683	0.594
Residual Std. Error	8.016	7.825
F Statistic	44083.188***	29970.462***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 16: 077-2010 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		-4.593***
		(0.096)
PurpleAir IDW Average	0.951***	1.147***
	(0.003)	(0.005)
Preferred	No	Yes
Observations	18,026	18,026
R^2	0.825	0.736
Adjusted R^2	0.825	0.736
Residual Std. Error	8.238	7.760
F Statistic	84882.128***	50316.689***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 17: 083-0011 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		7.949***
		(0.035)
PurpleAir IDW Average	0.009***	0.003***
	(0.000)	(0.000)
Preferred	No	Yes
Observations	33,171	33,171
R^2	0.050	0.015
Adjusted R^2	0.050	0.015
Residual Std. Error	10.052	6.334
F Statistic	1762.982***	519.691***
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 18: 103-0007 NAAQS Monitor PM2.5 on Weighted Average PurpleAir PM2.5

	Reported NAAQS Monitor PM2.5	
	(1)	(2)
const		9.376***
		(0.128)
PurpleAir IDW Average	0.150***	0.097***
	(0.003)	(0.003)
Preferred	No	Yes
Observations	25,260	25,260
R^2	0.110	0.054
Adjusted R^2	0.110	0.054
Residual Std. Error	21.525	19.560
F Statistic	3126.880***	1453.660***
Note:		*p<0.1; **p<0.05; ***p<0.01

The EPA AQS data system used to get the NAAQS monitor PM2.5 hourly readings uses data qualifier flags to describe what readings need to be excluded from calculations. Below are all the "NULL" and "REQEXC" type qualifiers, representing null/canceled data and requests for exceptional event designation. All data with REQEXC flags were removed from the analysis, and all data with NULL type flags have empty readings in the dataset and were treated as missing for replacement by PurpleAir PM2.5 measurement.

Table 19: Null and excluded EPA AQS data qualifier flags.

Qualifier Code	Qualifier Description	Qualifier Type Code
AA	Sample Pressure out of Limits.	NULL
AB	Technician Unavaliable.	NULL
AC	Construction/Repairs in Area.	NULL
AD	Shelter Storm Damage.	NULL
AE	Shelter Temperature Outside Limits.	NULL
AF	Scheduled but not Collected.	NULL
AG	Sample Time out of Limits.	NULL
AH	Sample Flow Rate or CV out of Limits.	NULL
AI	Insufficient Data (cannot calculate).	NULL
AJ	Filter Damage.	NULL
AK	Filter Leak.	NULL
AL	Voided by Operator.	NULL
AM	Miscellaneous Void.	NULL
AN	Machine Malfunction.	NULL
AO	Bad Weather.	NULL
AP	Vandalism.	NULL
AQ	Collection Error.	NULL
AR	Lab Error.	NULL
AS	Poor Quality Assurance Results.	NULL

AT	Calibration.	NULL
AU	Monitoring Waived.	NULL
AV	Power Failure.	NULL
AW	Wildlife Damage.	NULL
AX	Precision Check.	NULL
AY	Q C Control Points (zero/span).	NULL
AZ	Q C Audit.	NULL
BA	Maintenance/Routine Repairs.	NULL
BB	Unable to Reach Site.	NULL
BC	Multi-point Calibration.	NULL
BD	Auto Calibration.	NULL
BE	Building/Site Repair.	NULL
BF	Precision/Zero/Span.	NULL
BG	Missing ozone data not likely to exceed level of standard.	NULL
BH	Interference/co-elution/misidentification.	NULL
BI	Lost or damaged in transit.	NULL
BJ	Operator Error.	NULL
BK	Site computer/data logger down.	NULL
BL	QA Audit.	NULL
BM	Accuracy check.	NULL
BN	Sample Value Exceeds Media Limit.	NULL
BR	Sample Value Below Acceptable Range.	NULL
CS	Laboratory Calibration Standard.	NULL
DA	Aberrant Data (Corrupt Files, Aberrant Chromatography, Spikes, Shifts).	NULL
DL	Detection Limit Analyses.	NULL

EC	Exceeds Critical Criteria.	NULL
FI	Filter Inspection Flag.	NULL
MB	Method Blank (Analytical).	NULL
MC	Module End Cap Missing.	NULL
QV	Quality Control Multi-point Verification.	NULL
SA	Storm Approaching.	NULL
SC	Sampler Contamination.	NULL
ST	Calibration Verification Standard.	NULL
SV	Sample Volume out of limits.	NULL
TC	Component Check & Retention Time Standard.	NULL
TS	Holding Time Or Transport Temperature Is Out Of Specs.	NULL
XX	Experimental Data.	NULL
1C	A 1-Point QC check exceeds acceptance criteria but there is compelling evidence that the analyzer data is valid.	NULL QC
1F	No 1 Point QC but need to count for completeness	NULL QC
E	Forest Fire.	REQEXC
RA	African Dust.	REQEXC
RB	Asian Dust.	REQEXC
RC	Chemical Spills & Industrial Accidents.	REQEXC
RD	Cleanup After a Major Disaster.	REQEXC
RE	Demolition.	REQEXC
RF	Fire - Canadian.	REQEXC
RG	Fire - Mexico/Central America.	REQEXC
RH	Fireworks.	REQEXC
RI	High Pollen Count.	REQEXC
RJ	High Winds.	REQEXC

RK	Infrequent Large Gatherings.	REQEXC
RL	Other.	REQEXC
RM	Prescribed Fire.	REQEXC
RN	Seismic Activity.	REQEXC
RO	Stratospheric Ozone Intrusion.	REQEXC
RP	Structural Fire.	REQEXC
RQ	Terrorist Act.	REQEXC
RR	Unique Traffic Disruption.	REQEXC
RS	Volcanic Eruptions.	REQEXC
RT	Wildfire-U. S.	REQEXC
RU	Wildland Fire Use Fire-U. S.	REQEXC

6.5 Pictures of PM2.5 monitors

Figure 6: A typical NAAQS-primary grade air quality monitoring station.

Figure 7: One of PurpleAir's two main outdoor air pollution monitors.

6.6 Plots for Other California Hourly NAAQS Monitors

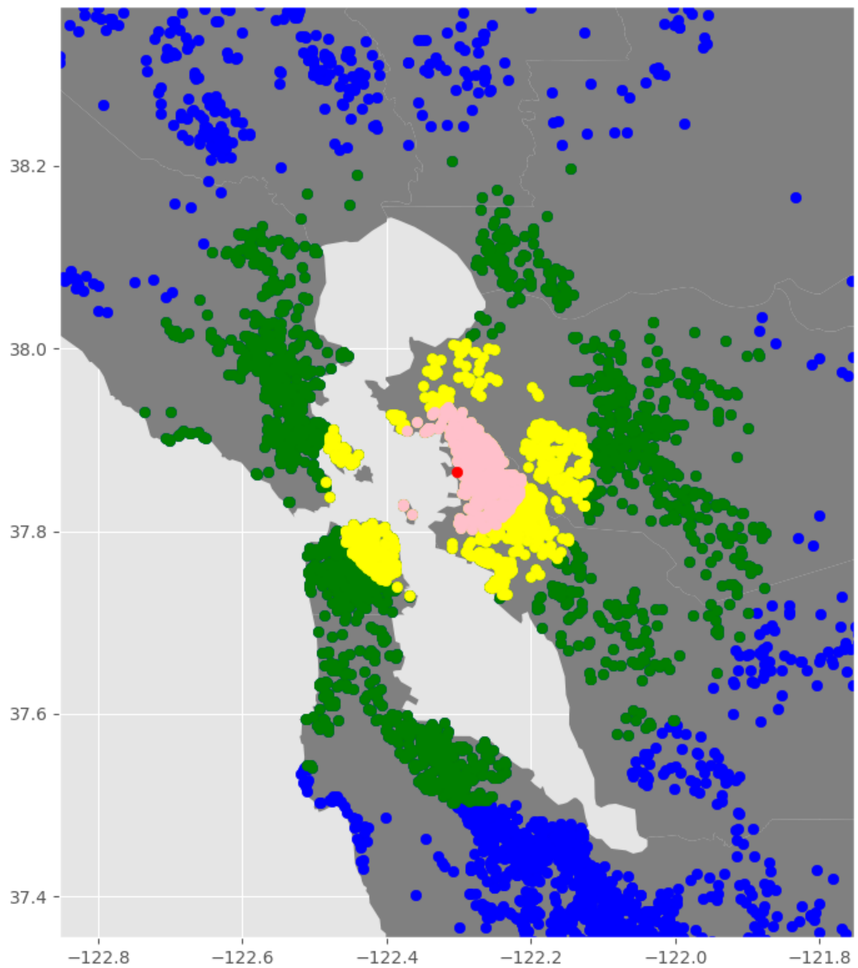

Figure 8: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0013 in county 001 (FIPS code).

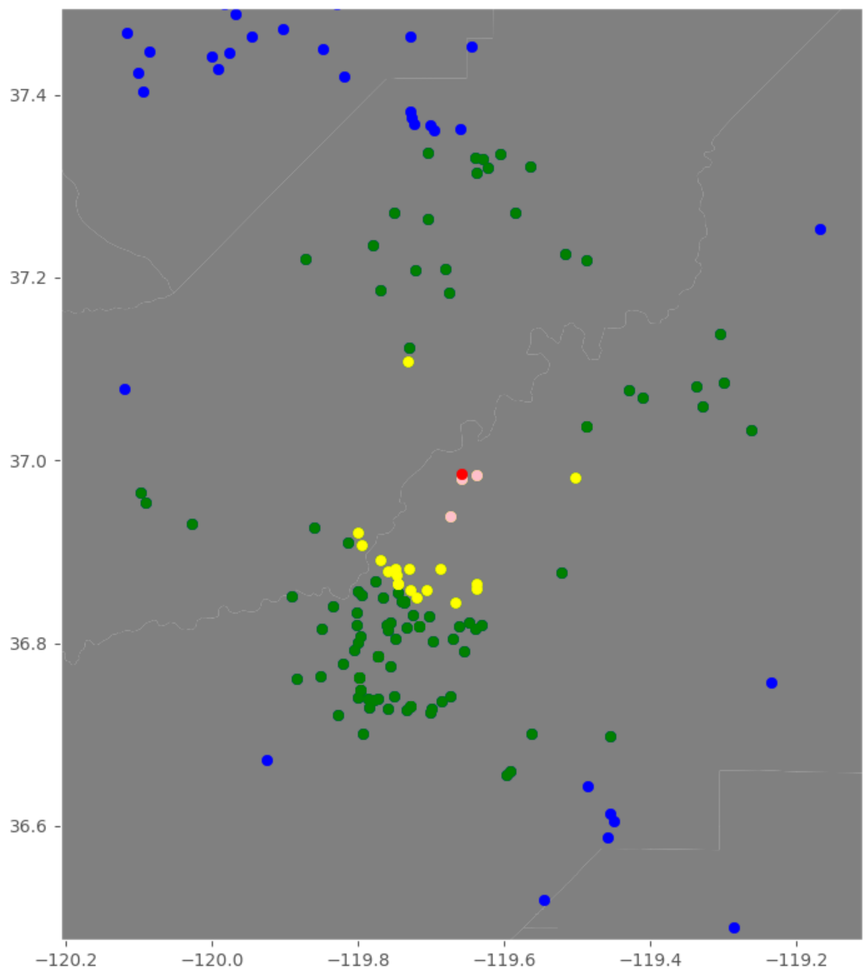

Figure 9: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0500 in county 019 (FIPS code).

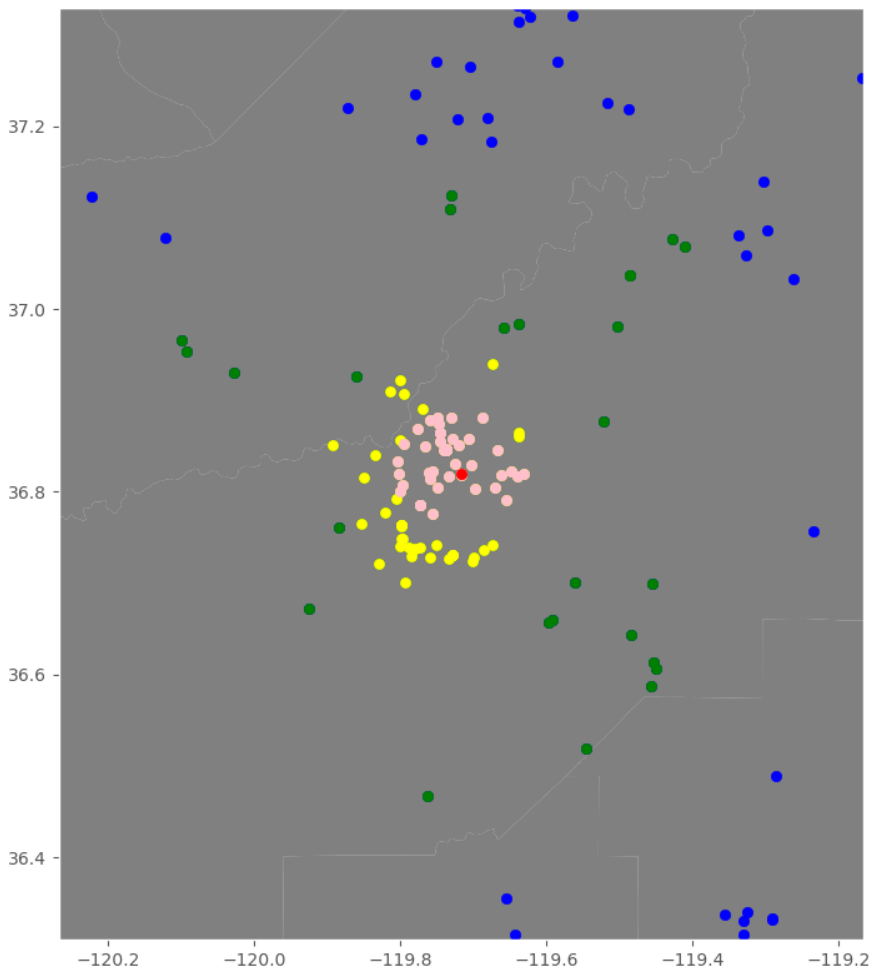

Figure 10: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 5001 in county 019 (FIPS code).

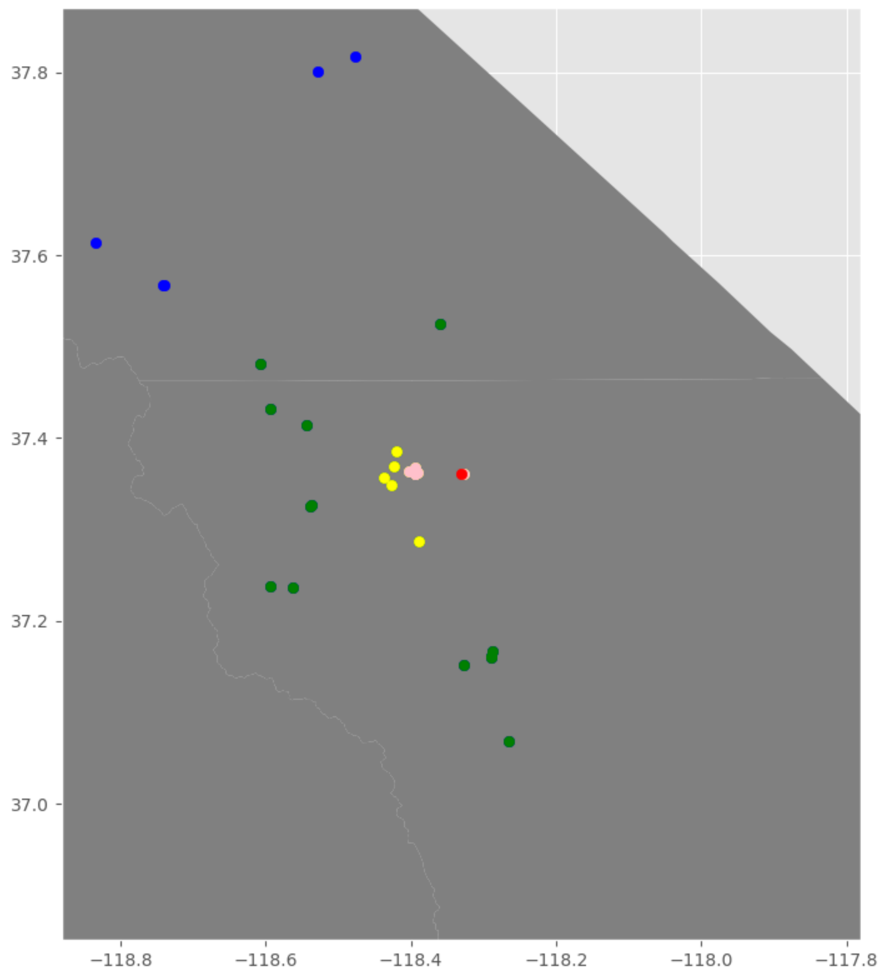

Figure 11: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0002 in county 027 (FIPS code).

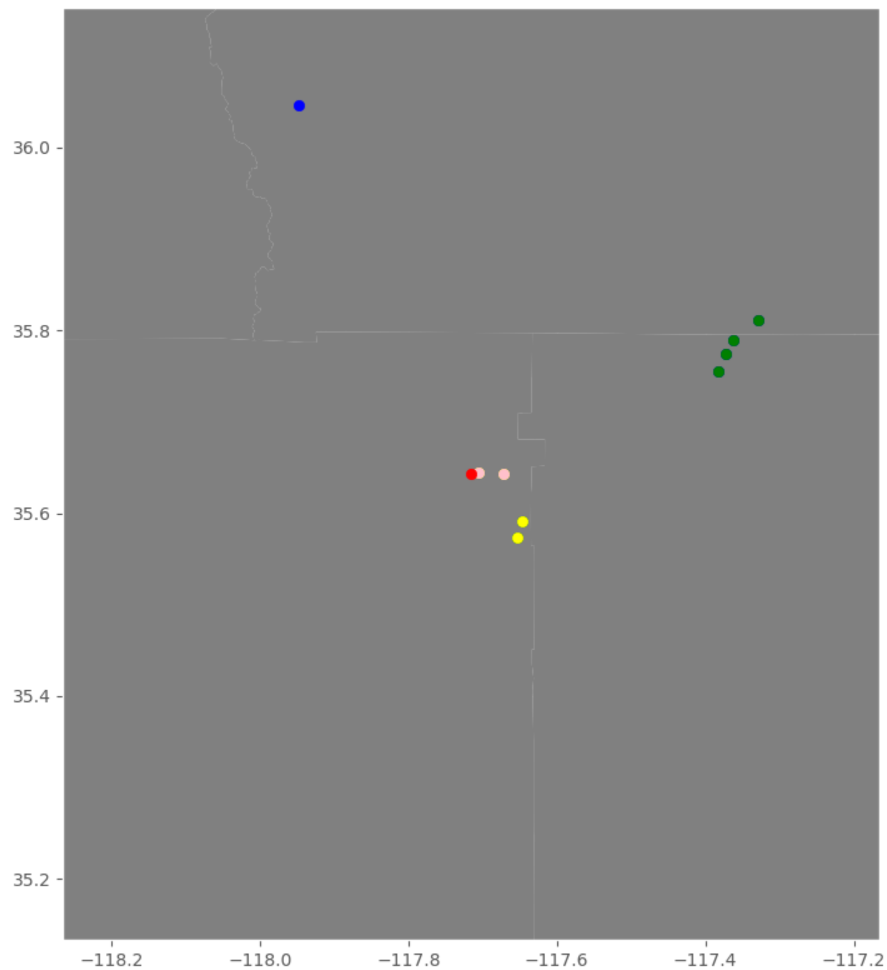

Figure 12: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0018 in county 029 (FIPS code).

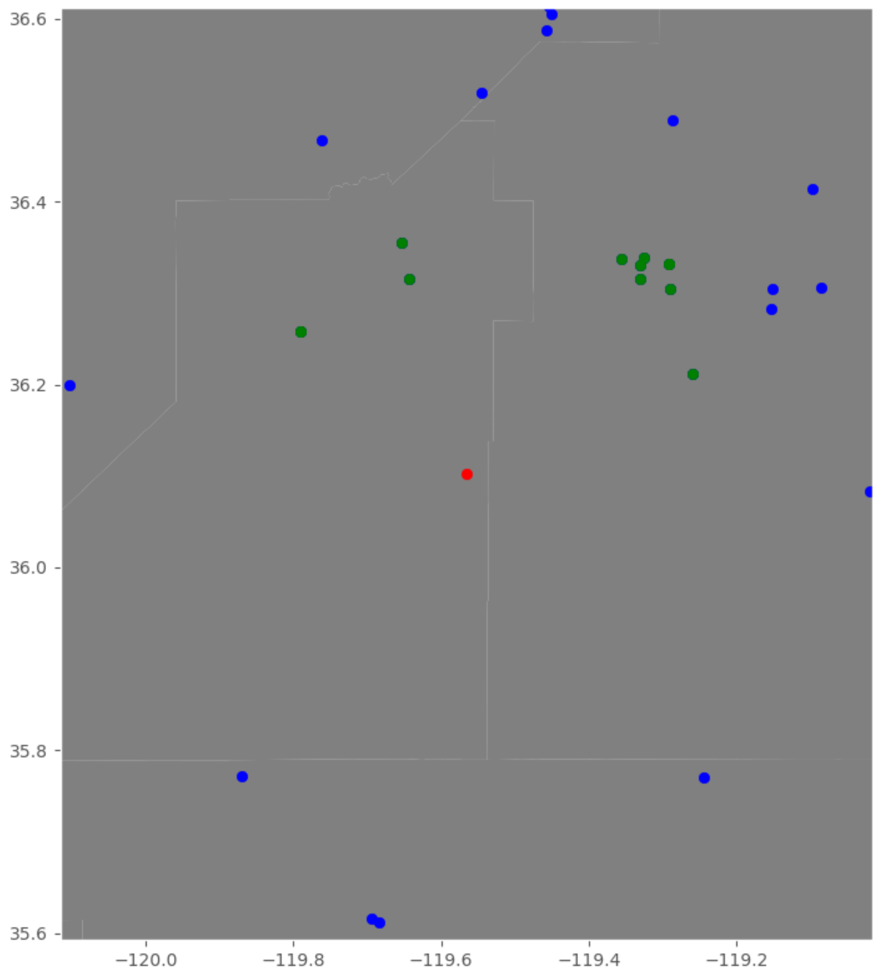

Figure 13: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0004 in county 031 (FIPS code).

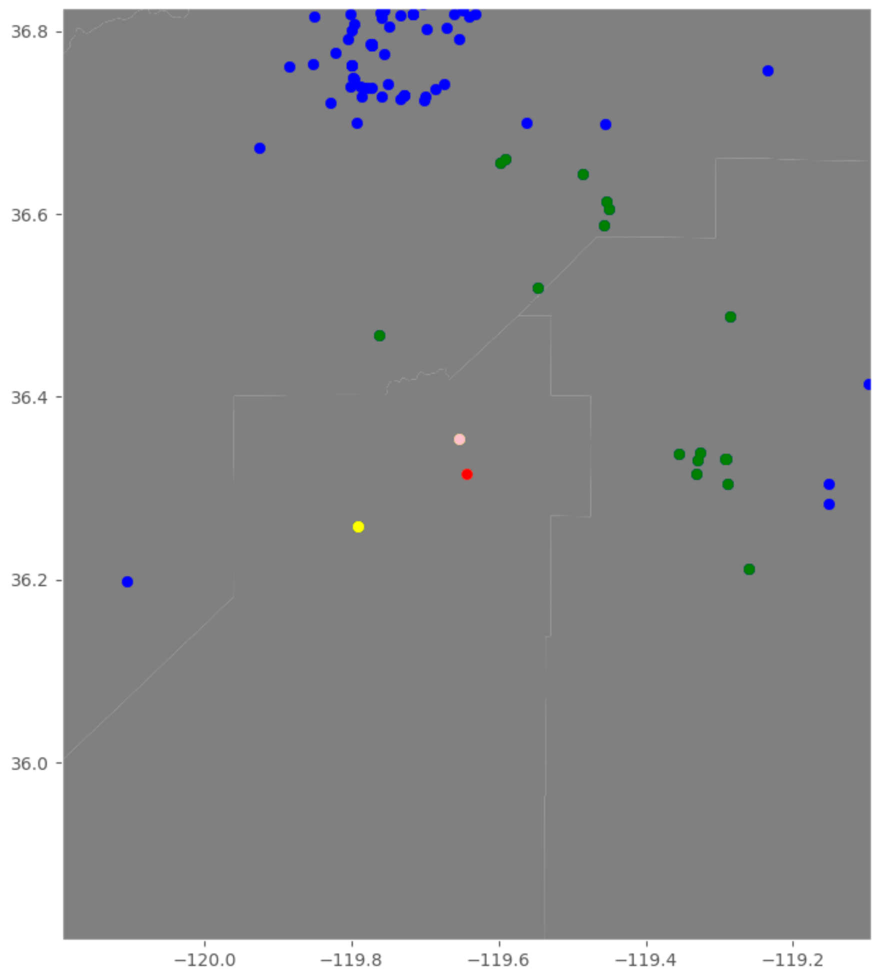

Figure 14: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 1004 in county 031 (FIPS code).

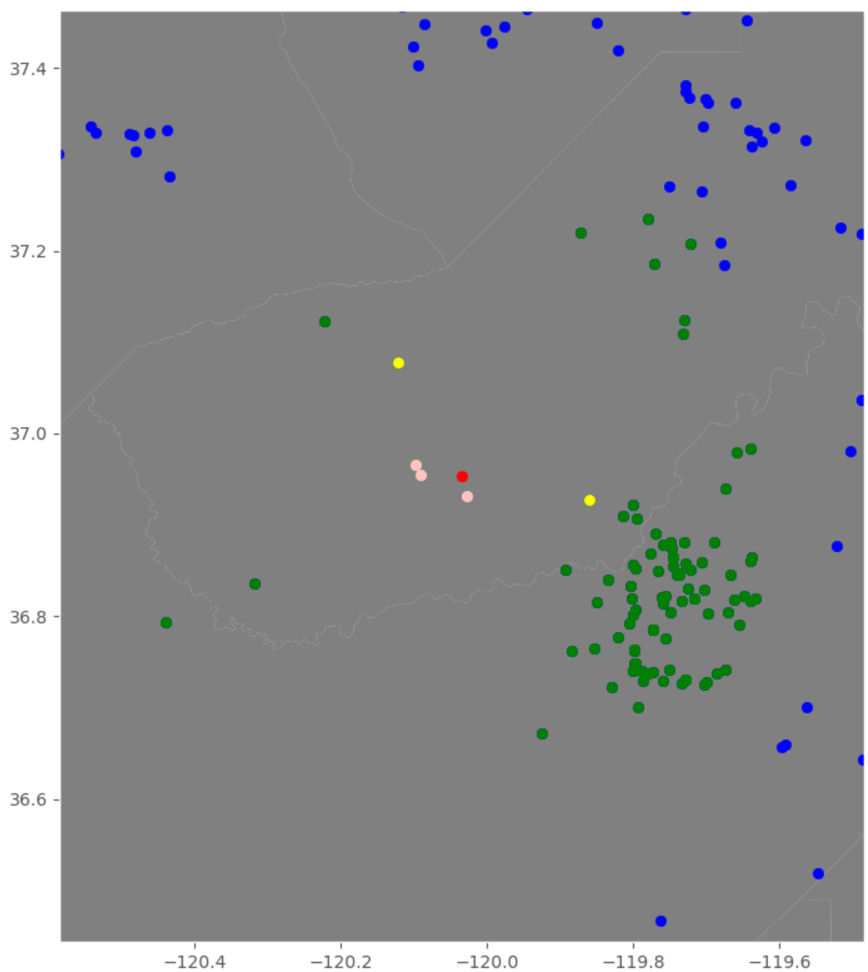

Figure 15: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 2010 in county 039 (FIPS code).

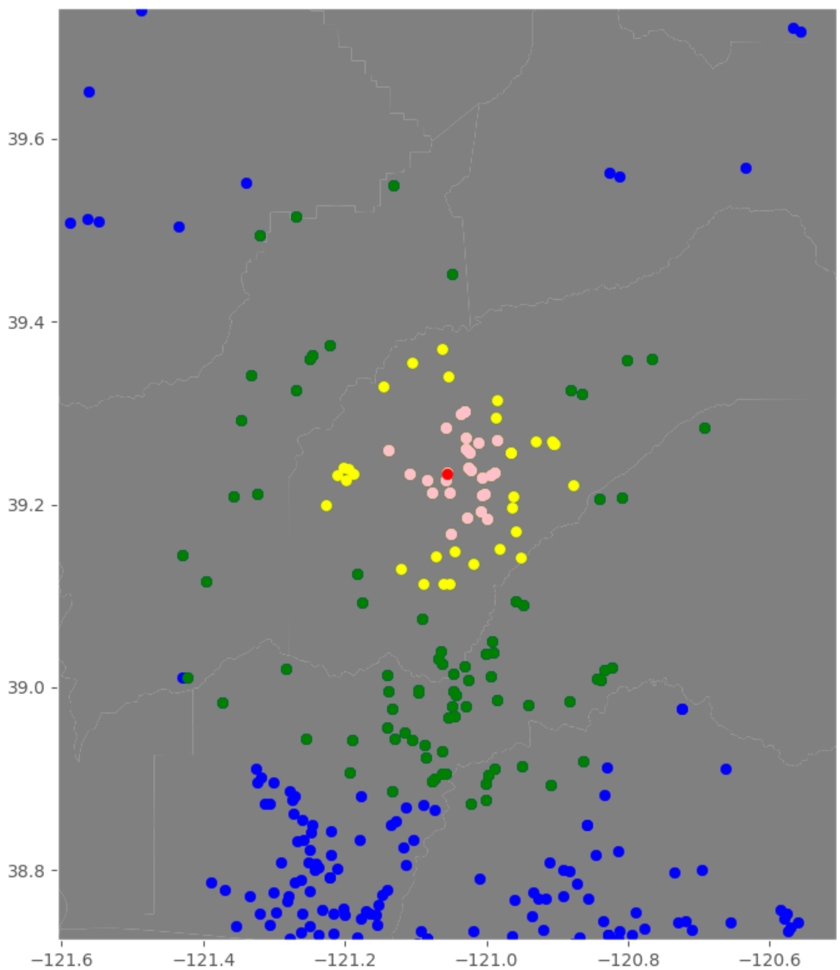

Figure 16: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0005 in county 057 (FIPS code).

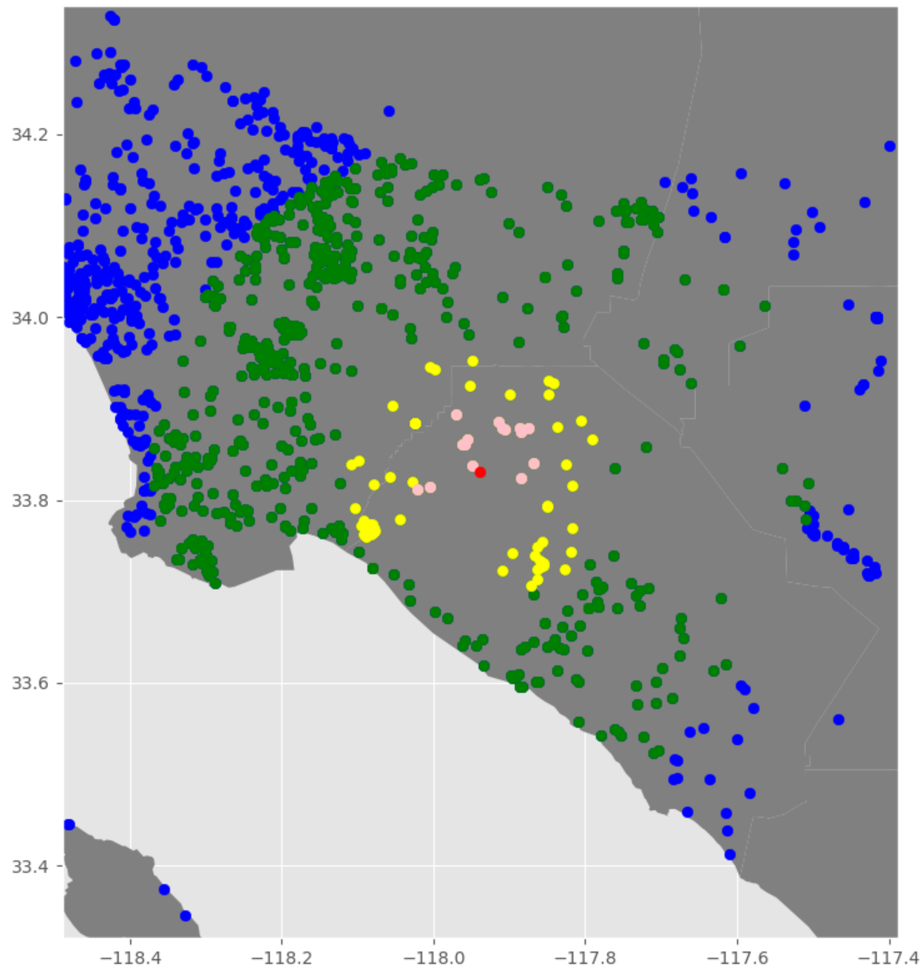

Figure 17: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0007 in county 059 (FIPS code).

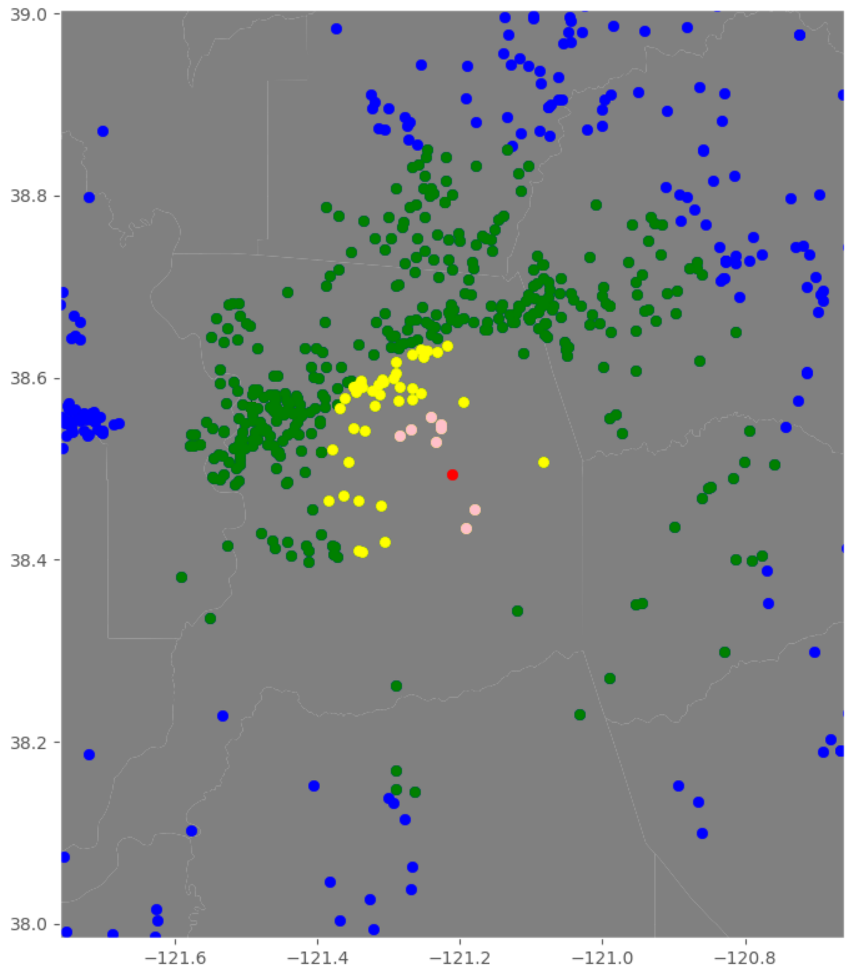

Figure 18: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 5003 in county 067 (FIPS code).

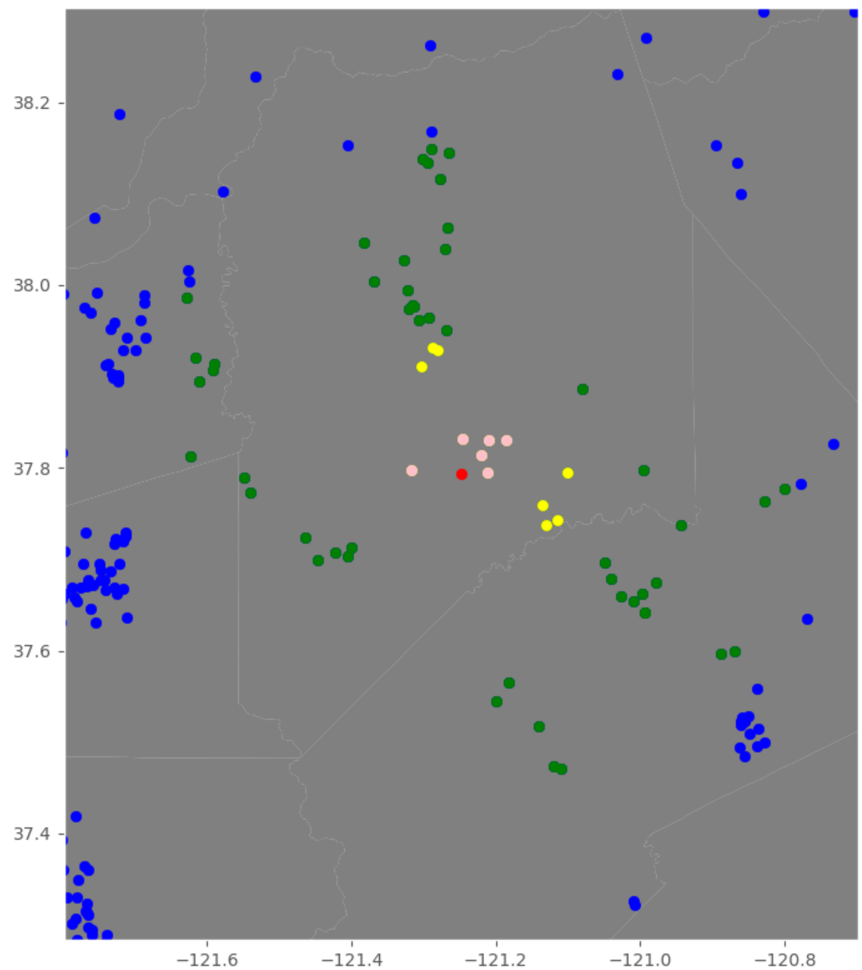

Figure 19: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 2010 in county 077 (FIPS code).

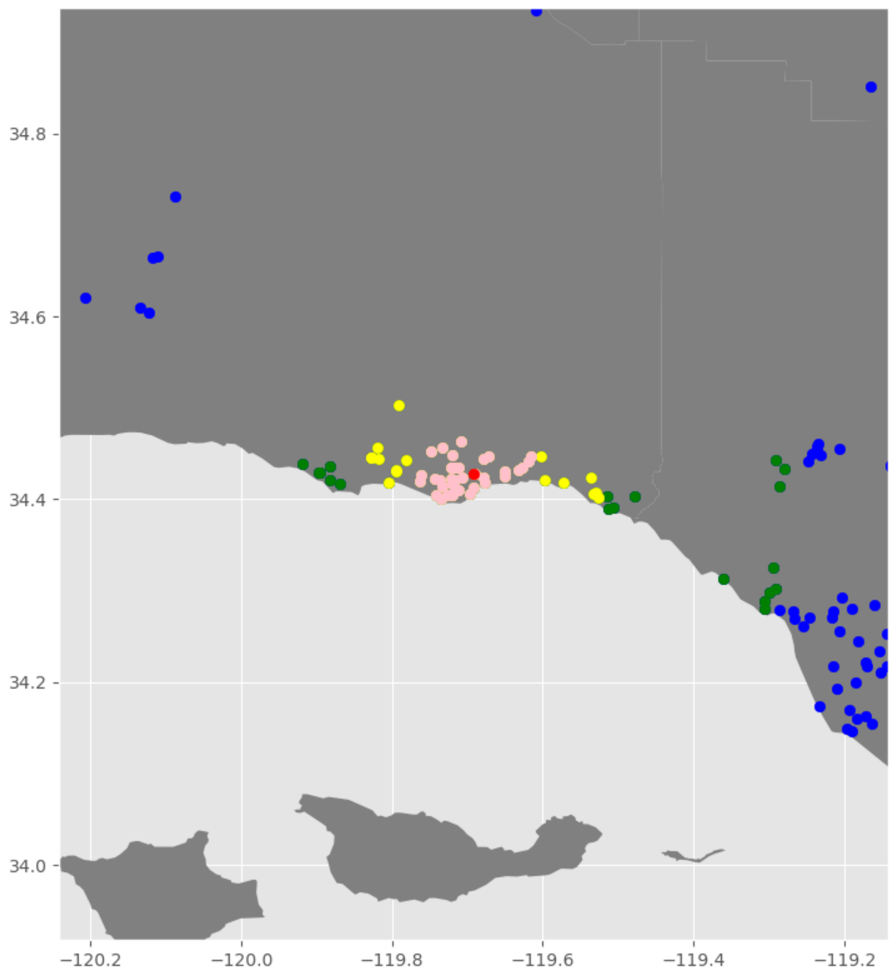

Figure 20: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0011 in county 083 (FIPS code).

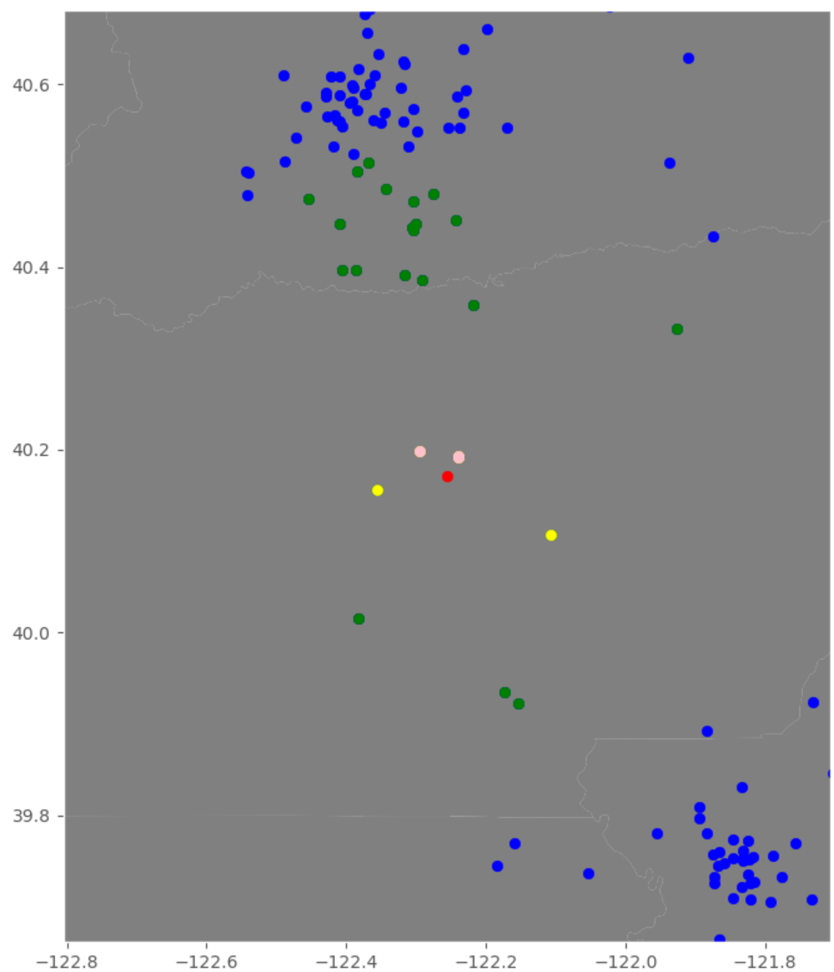

Figure 21: Map of EPA NAAQS-primary monitoring station (red) surrounded by PurpleAir monitors within 5-mile (pink), 10-mile (yellow), and 25-mile (green) radii.This preliminary analysis uses the PurpleAir sensors within 5 miles (pink markers). This monitor is at site 0007 in county 103 (FIPS code).

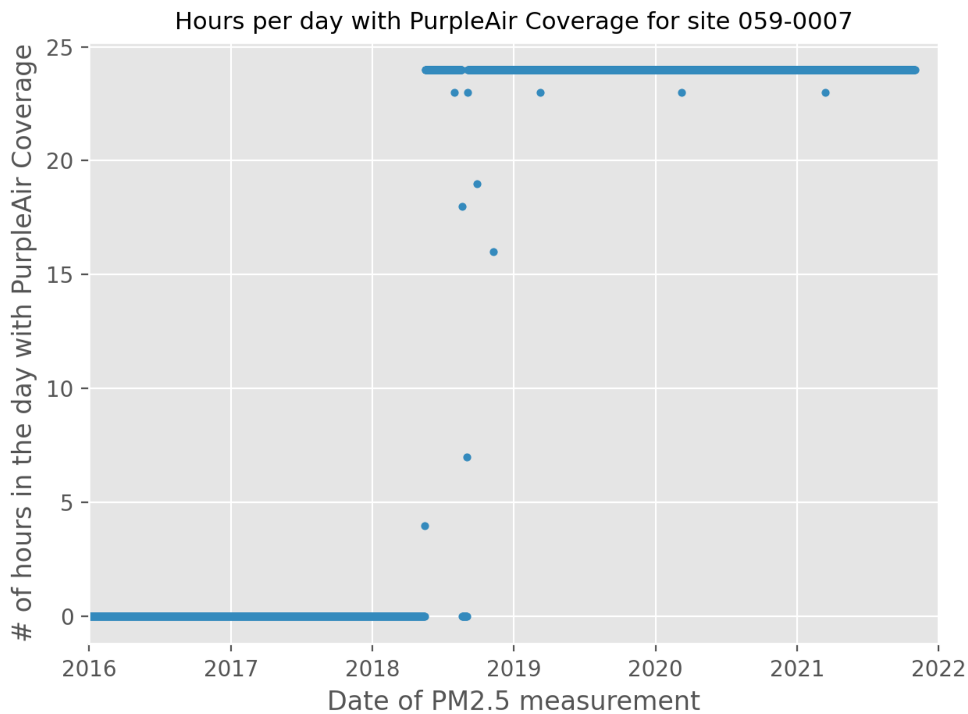

Figure 22: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0007 in county 059 (FIPS code).

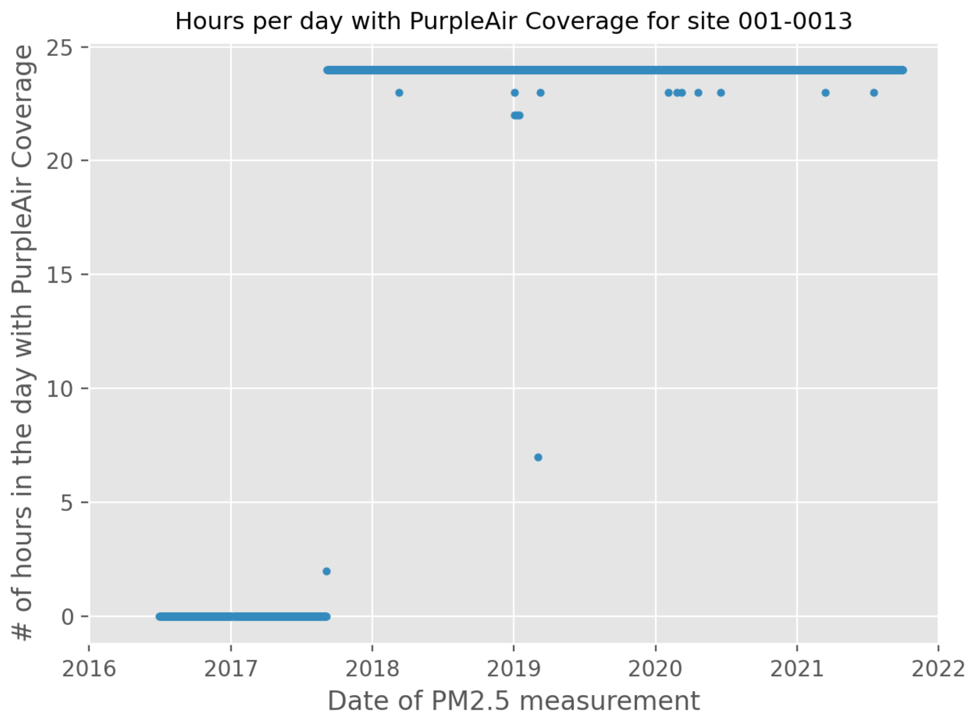

Figure 23: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0013 in county 001 (FIPS code).

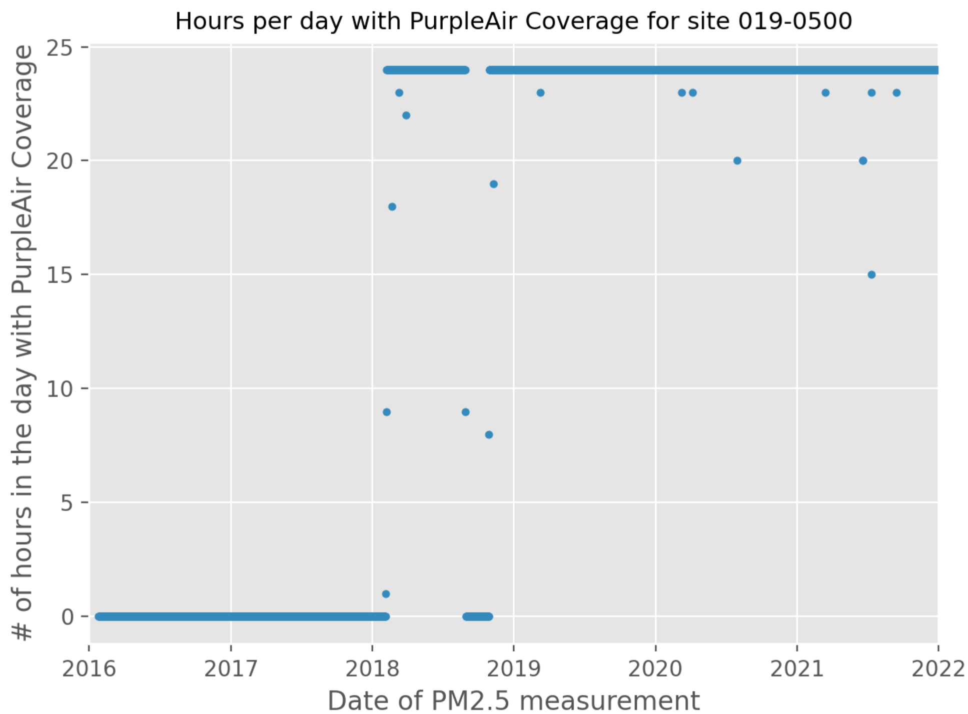

Figure 24: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0500 in county 019 (FIPS code).

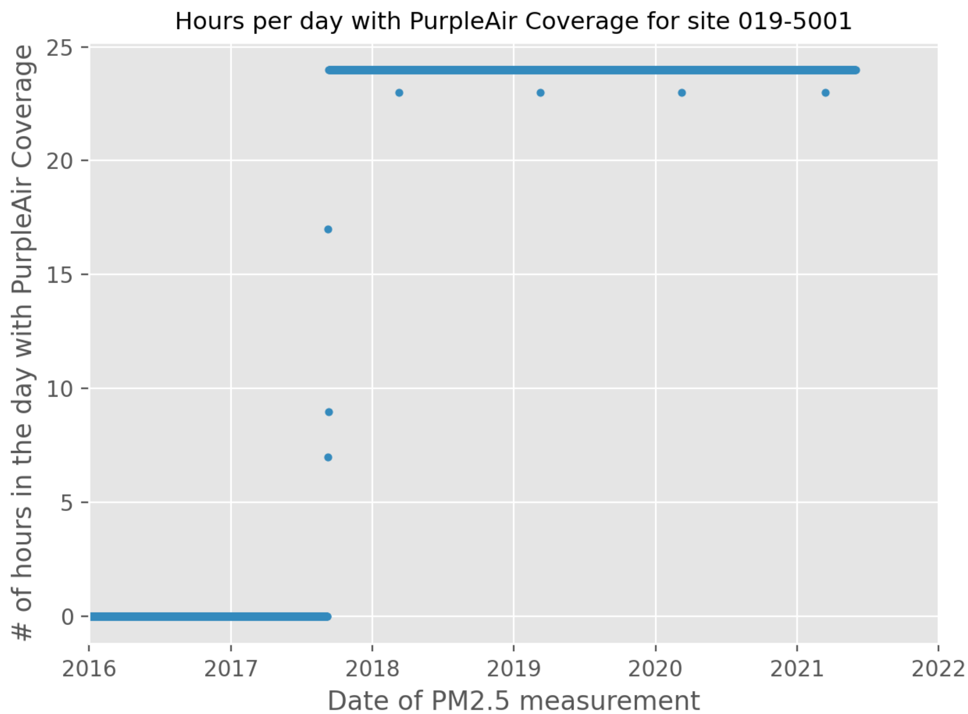

Figure 25: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 5001 in county 019 (FIPS code).

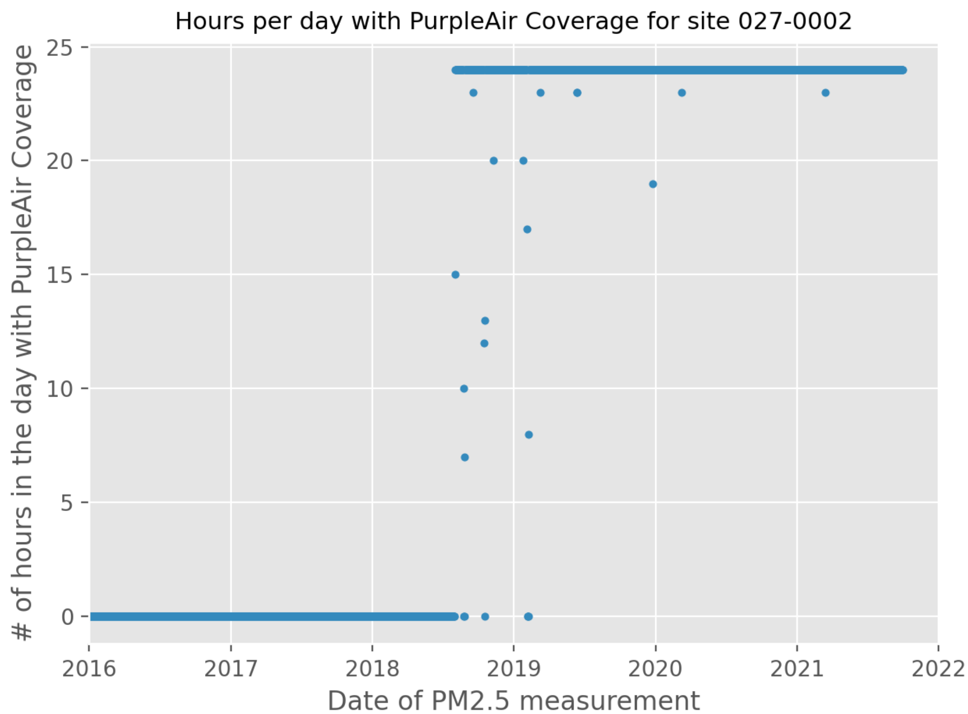

Figure 26: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0002 in county 027 (FIPS code).

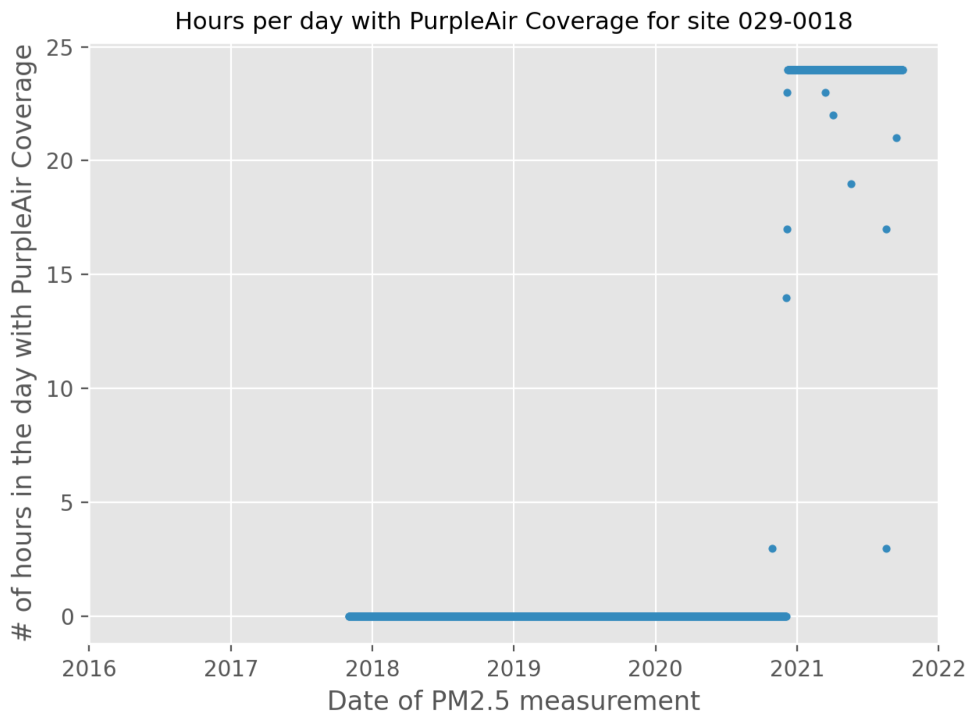

Figure 27: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0018 in county 029 (FIPS code).

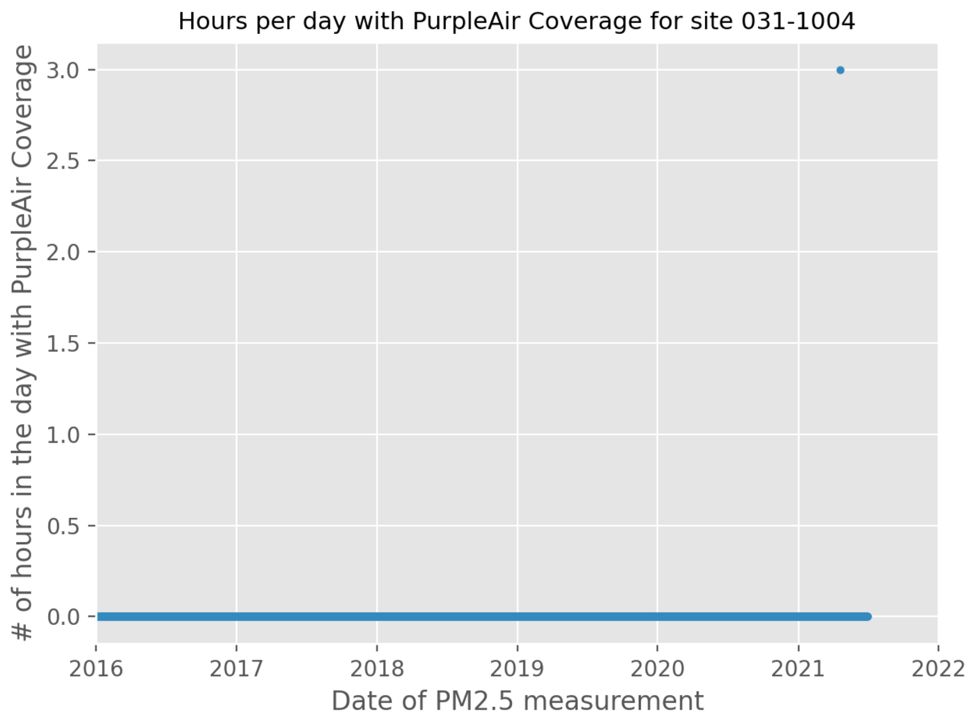

Figure 28: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 1004 in county 031 (FIPS code).

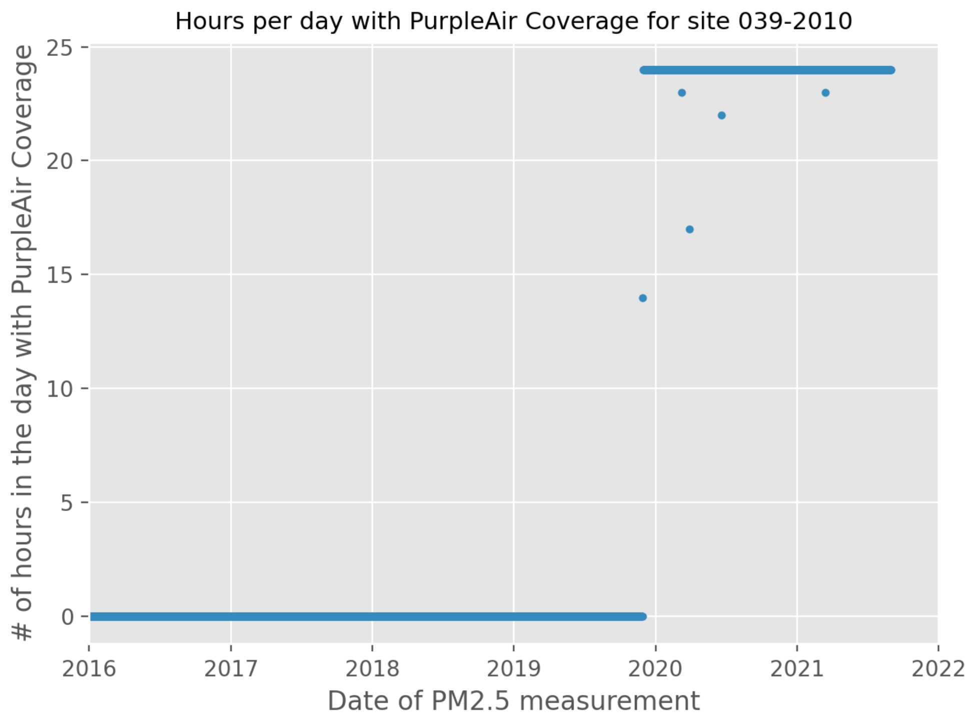

Figure 29: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 2010 in county 039 (FIPS code).

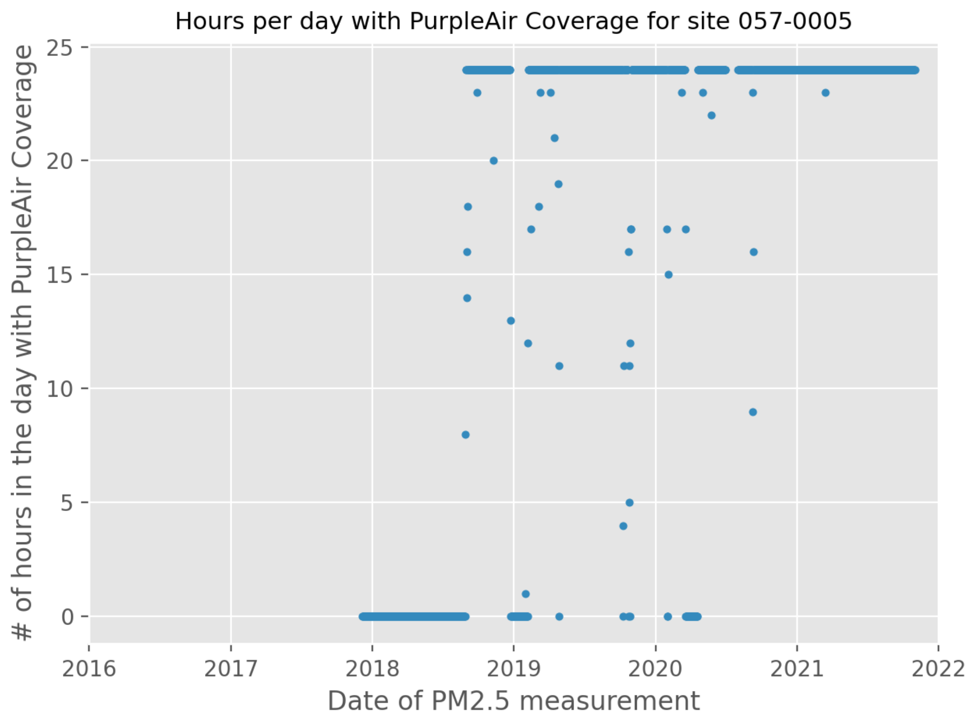

Figure 30: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0005 in county 057 (FIPS code).

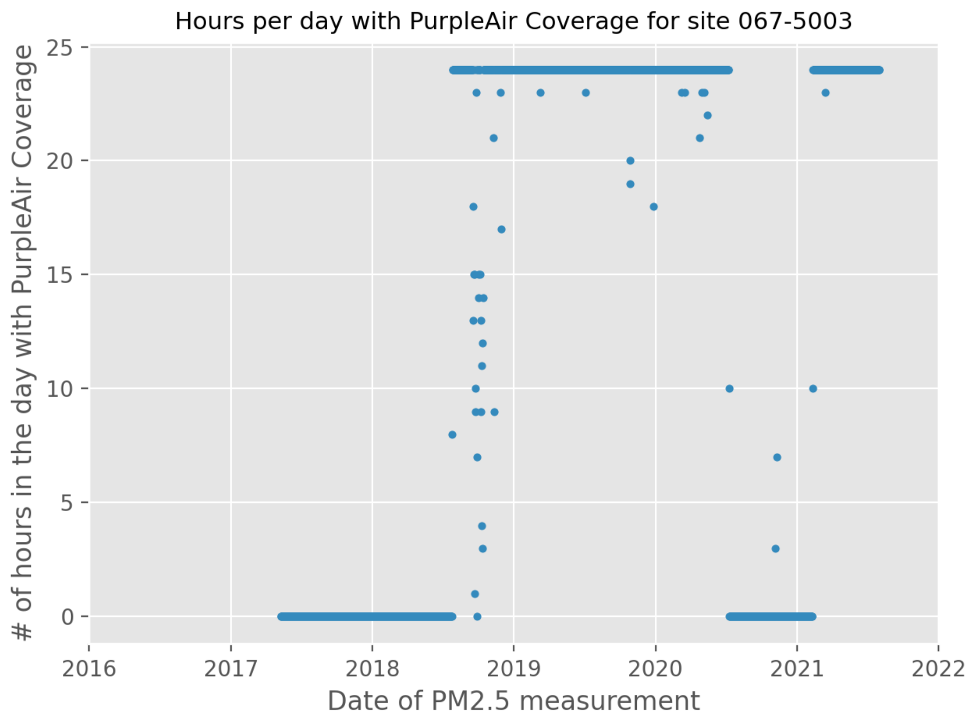

Figure 31: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 5003 in county 067 (FIPS code).

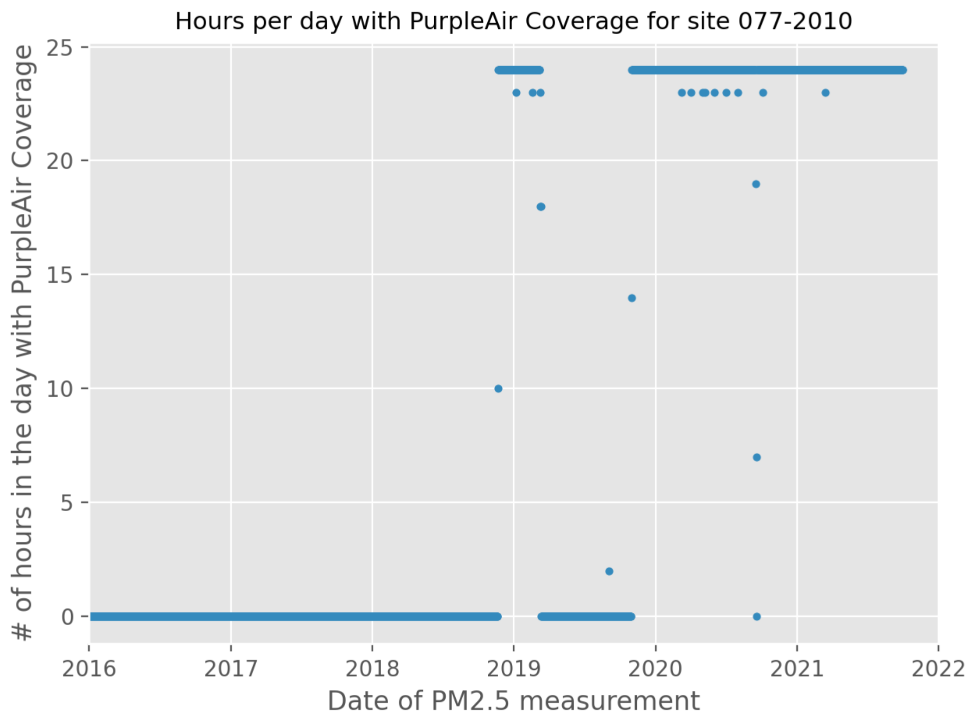

Figure 32: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 2010 in county 077 (FIPS code).

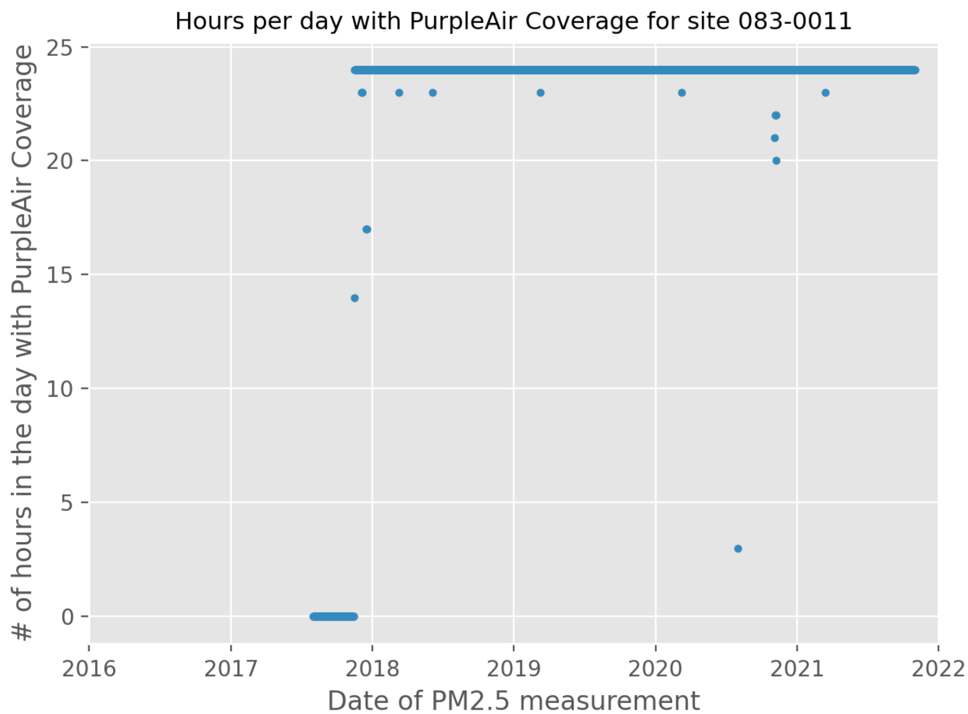

Figure 33: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0011 in county 083 (FIPS code).

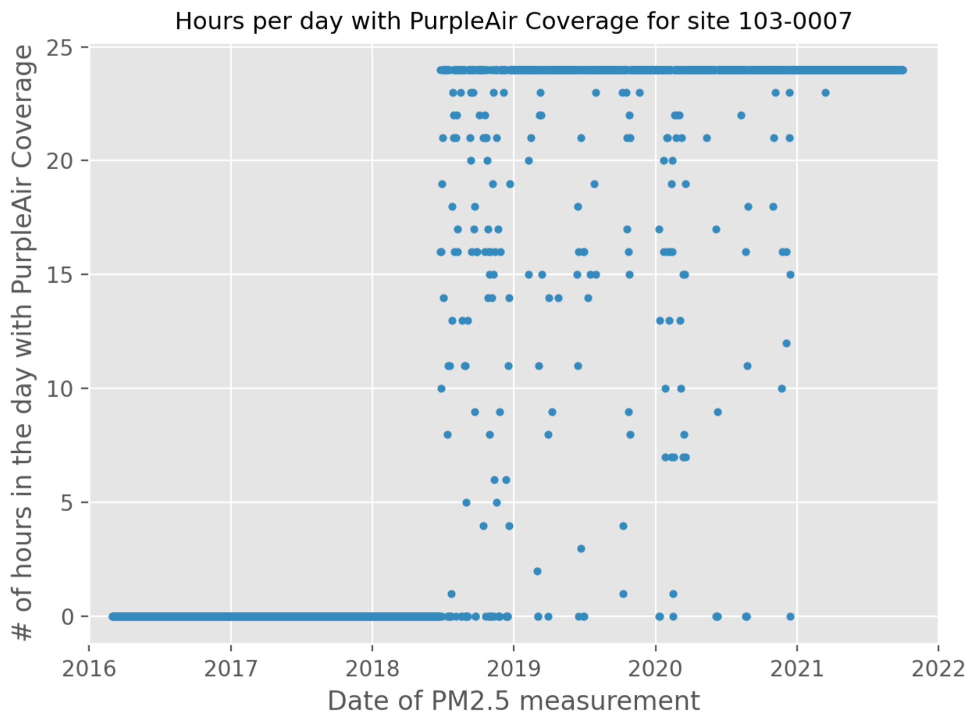

Figure 34: Scatter plot indicating the number of hours in each day that this NAAQS monitor has PurpleAir coverage. An hour has PurpleAir coverage if there are any PurpleAir sensor readings within the 5-mile radius of the monitor site for that hour. The weighted average is calculated for that hour using all the available PurpleAir readings within 5 miles. This monitor is at site 0007 in county 103 (FIPS code).

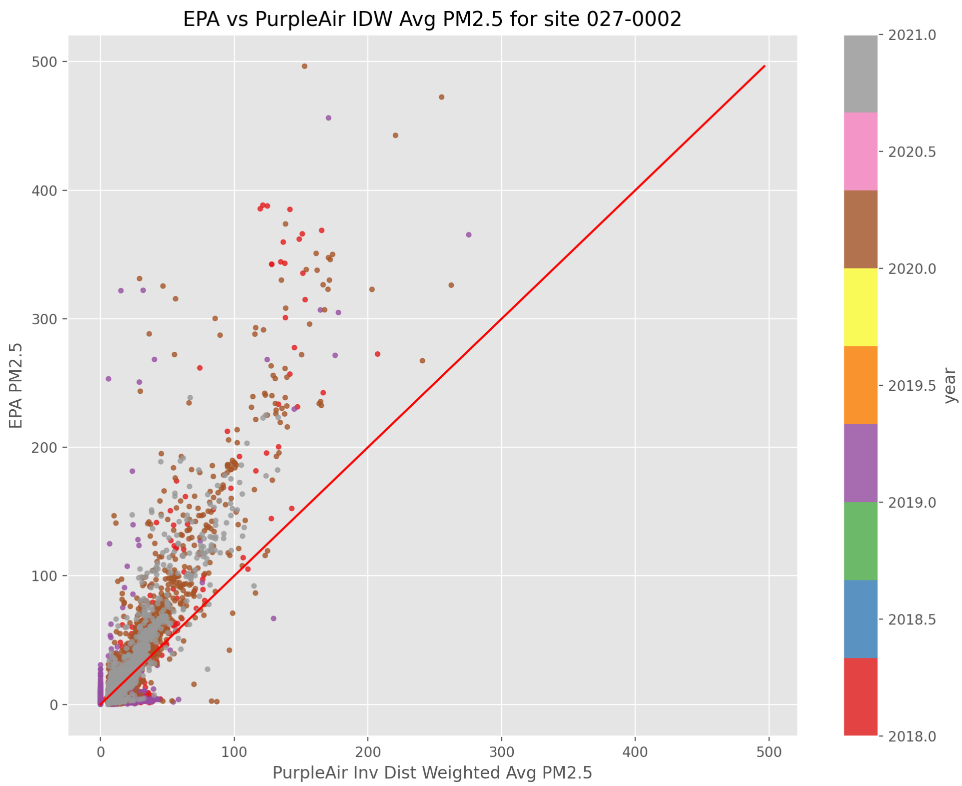

Figure 35: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0002 in county 027 (FIPS code).

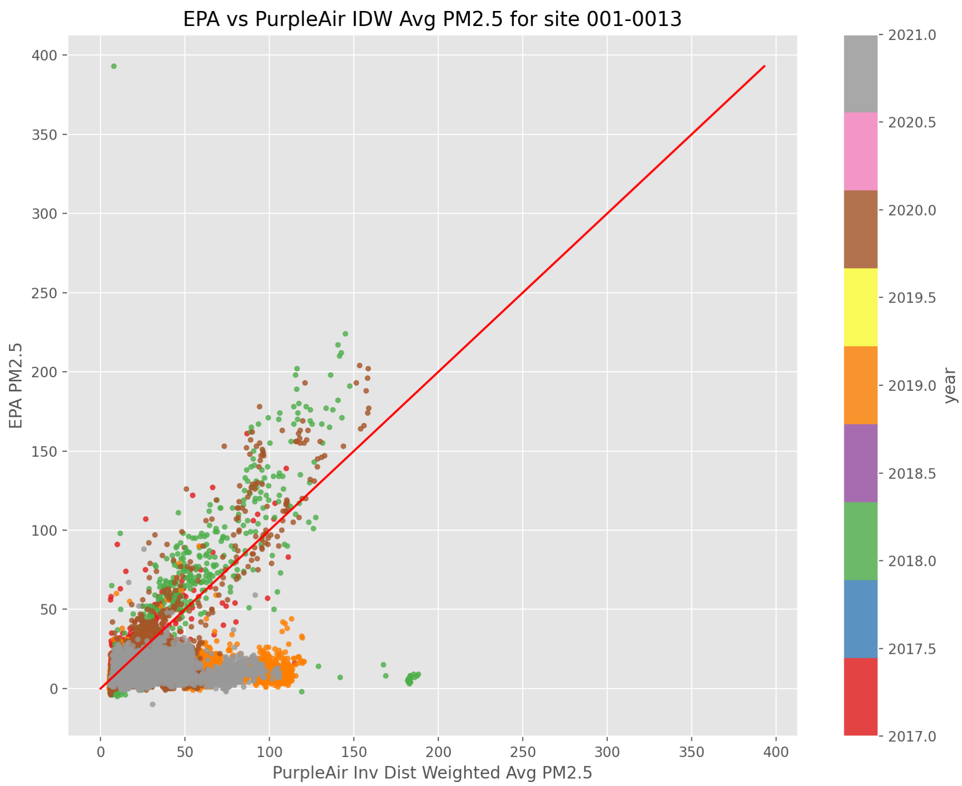

Figure 36: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0013 in county 001 (FIPS code).

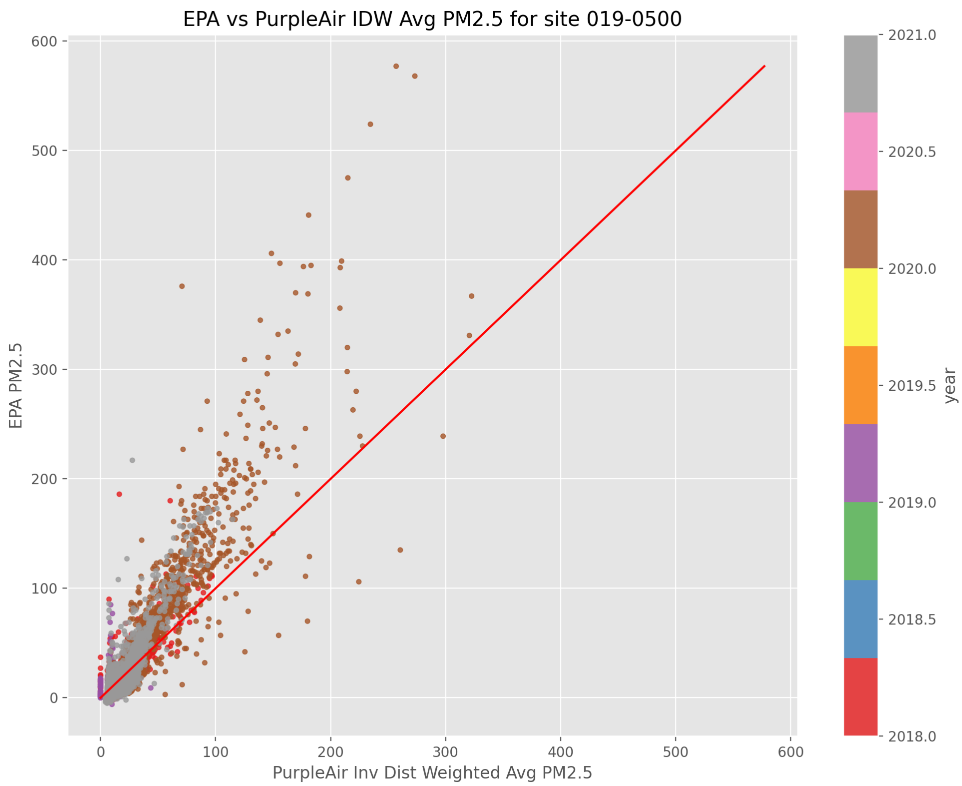

Figure 37: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0500 in county 019 (FIPS code).

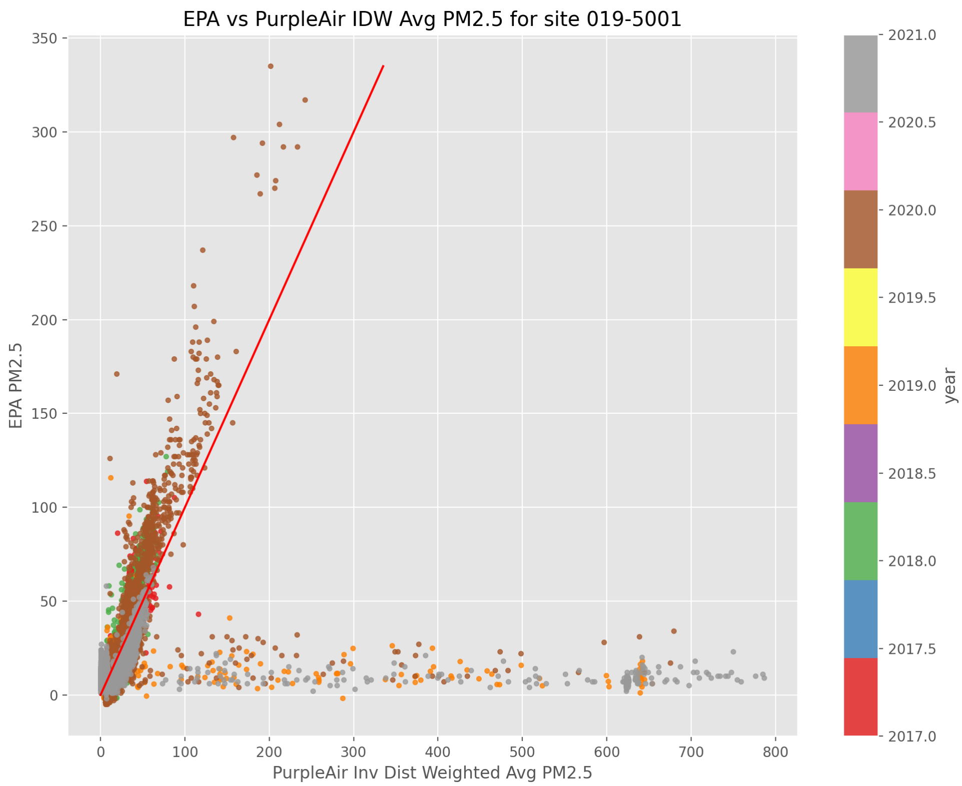

Figure 38: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 5001 in county 019 (FIPS code).

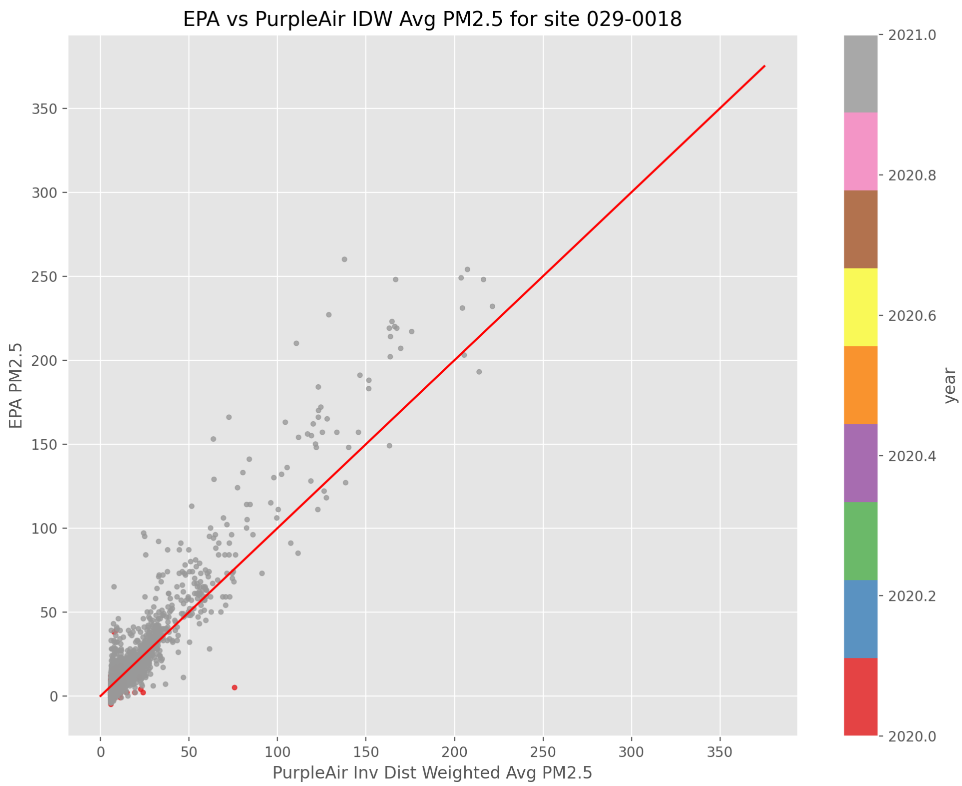

Figure 39: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0018 in county 029 (FIPS code).

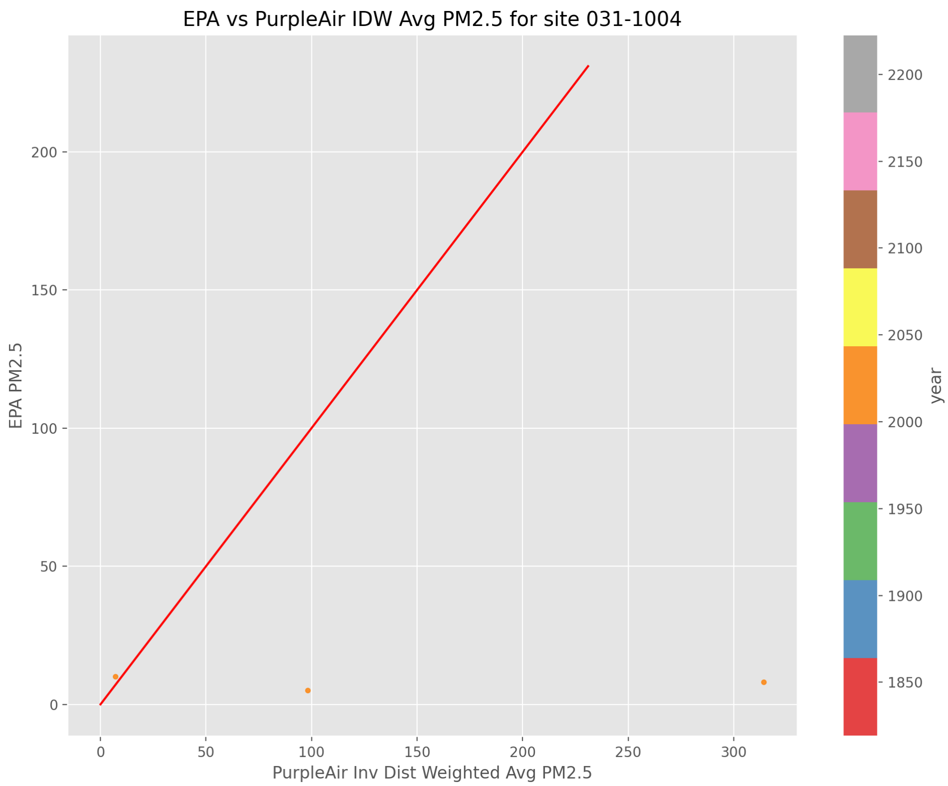

Figure 40: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 1004 in county 031 (FIPS code).

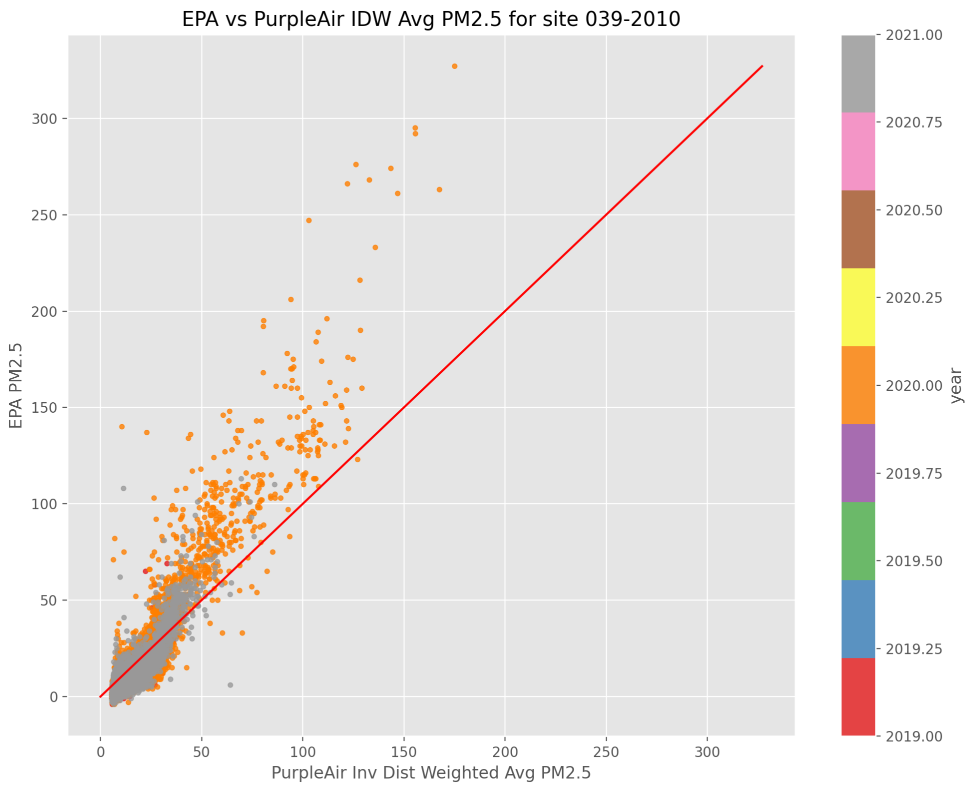

Figure 41: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 2010 in county 039 (FIPS code).

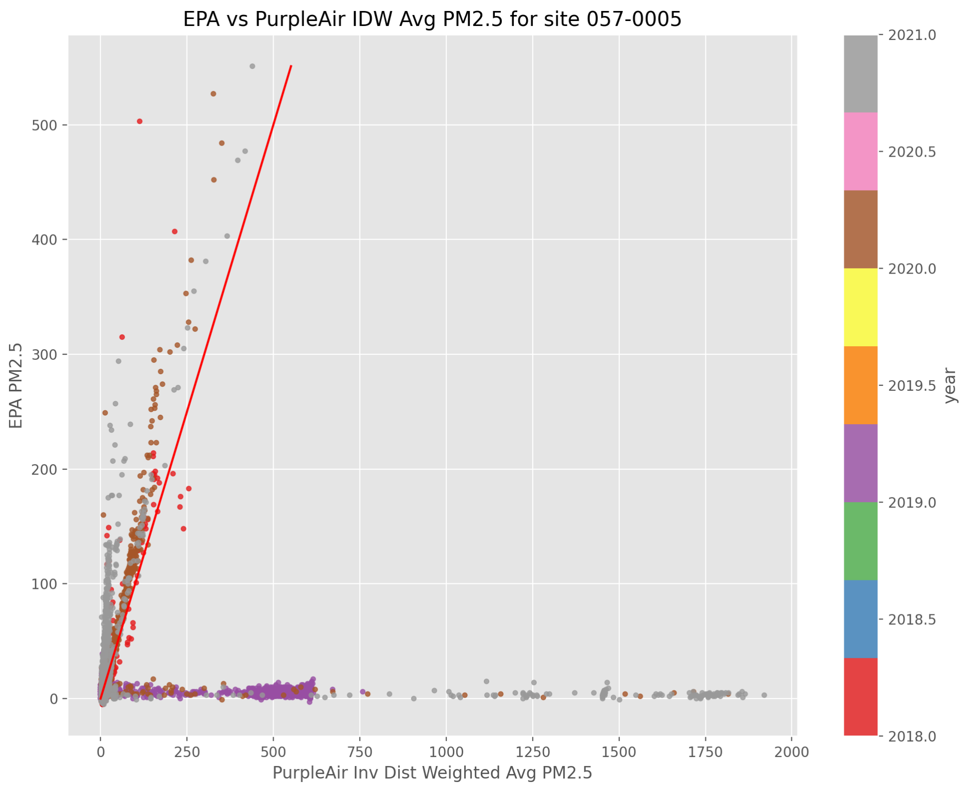

Figure 42: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0005 in county 057 (FIPS code).

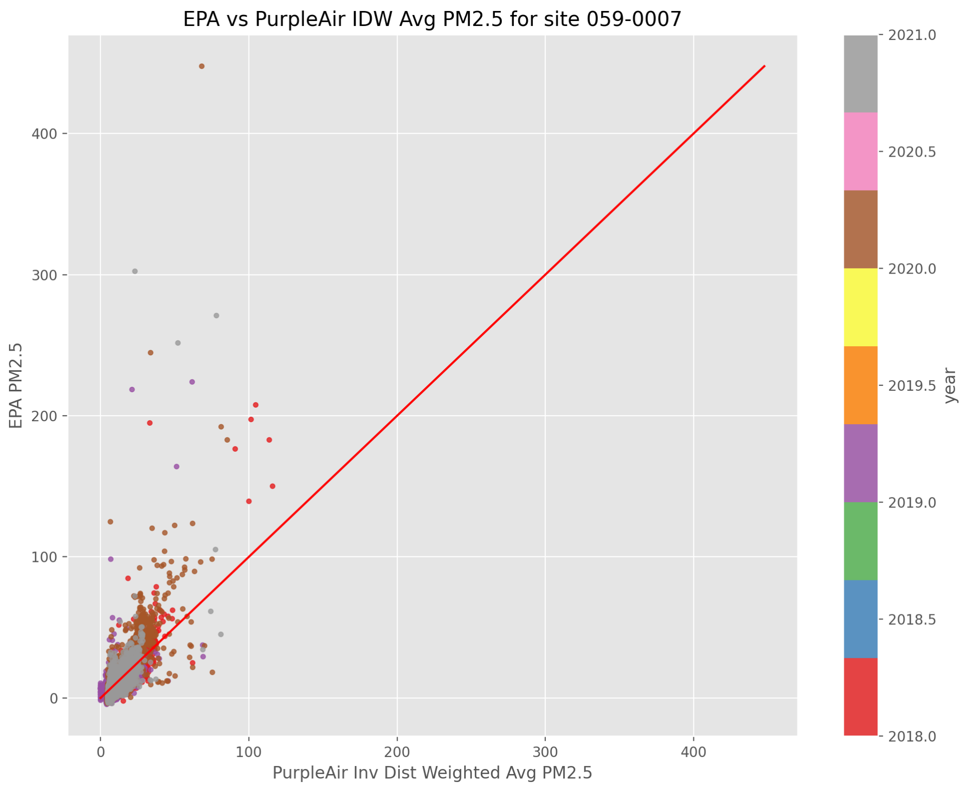

Figure 43: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0007 in county 059 (FIPS code).

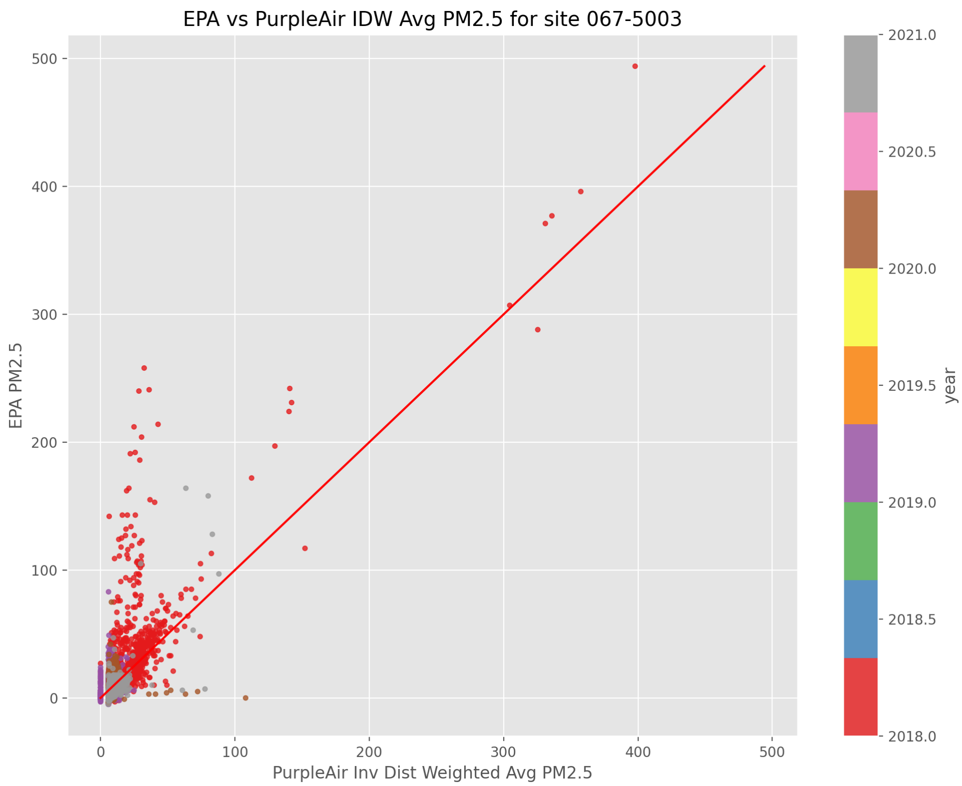

Figure 44: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 5003 in county 067 (FIPS code).

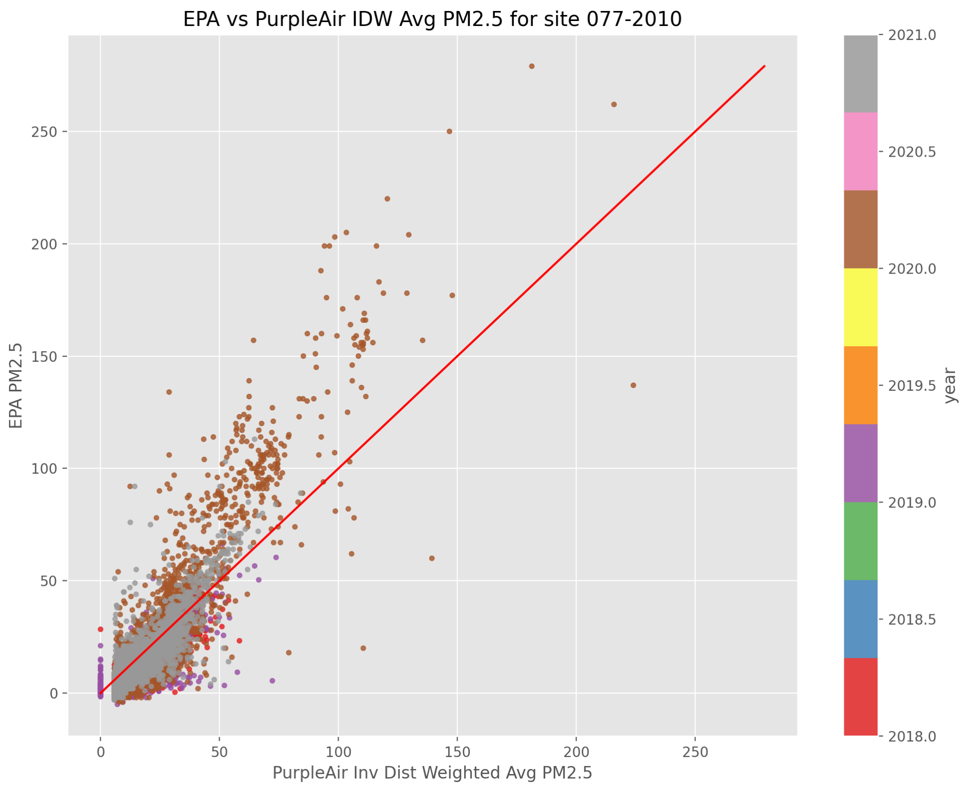

Figure 45: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 2010 in county 077 (FIPS code).

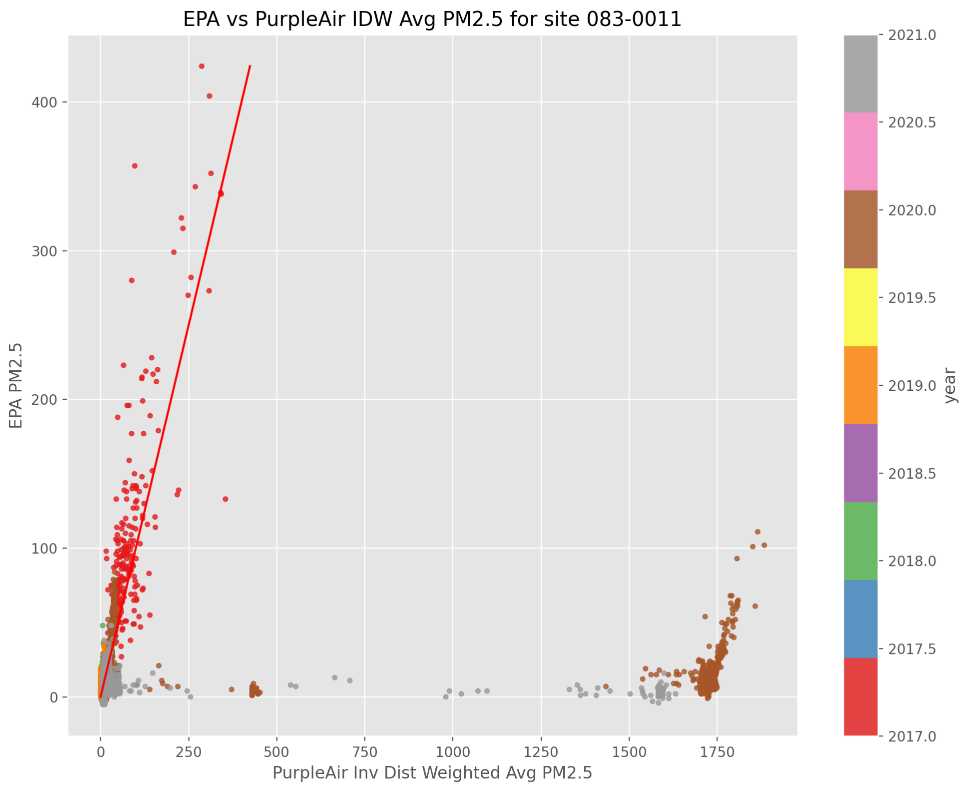

Figure 46: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0011 in county 083 (FIPS code).

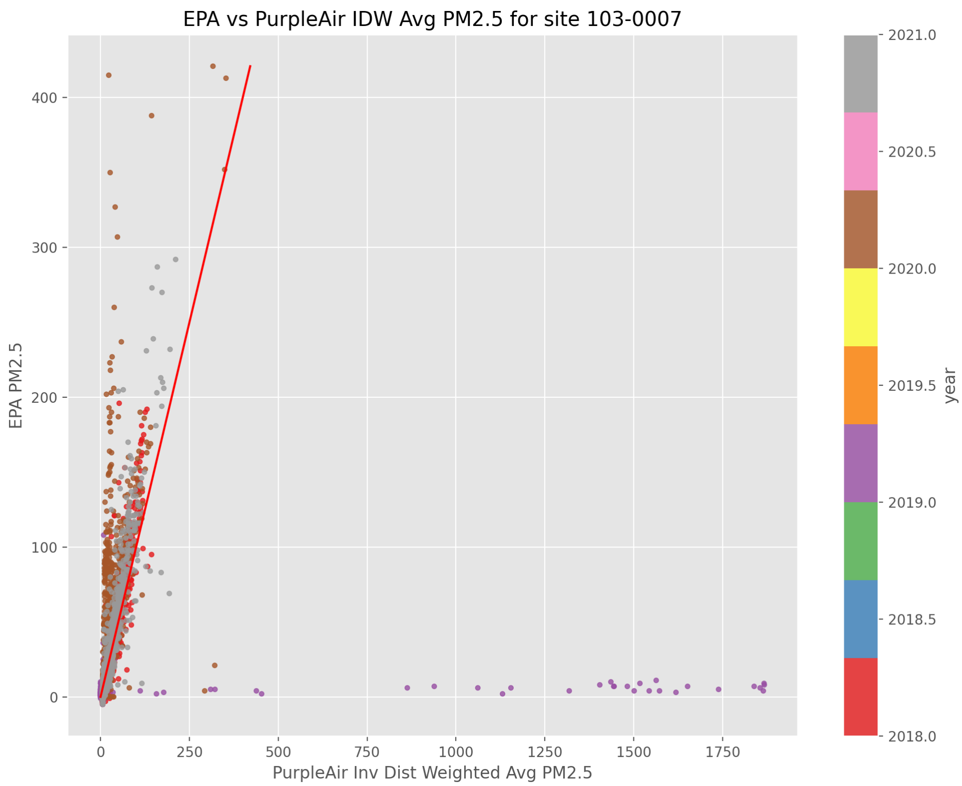

Figure 47: Scatter plot comparing reported hourly PM2.5 measurements: the x-axis represents the IDW-weighted average of PurpleAir measurements, the y-axis represents reported NAAQS-primary monitor measurements. The red line is a 45° line, representing perfect correlation between the PurpleAir average and the NAAQS-primary monitor. This monitor is at site 0007 in county 103 (FIPS code).

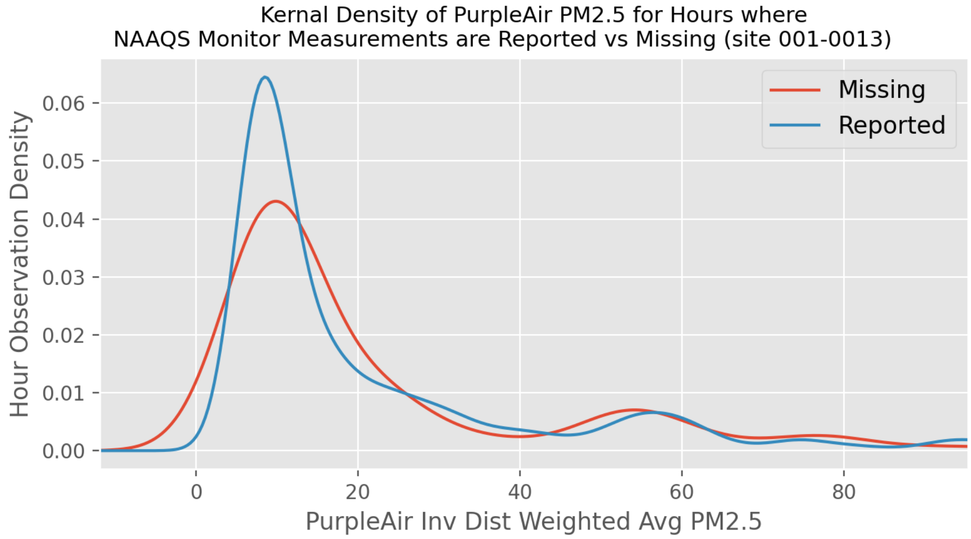

Figure 48: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 0013 in county 001 (FIPS code).

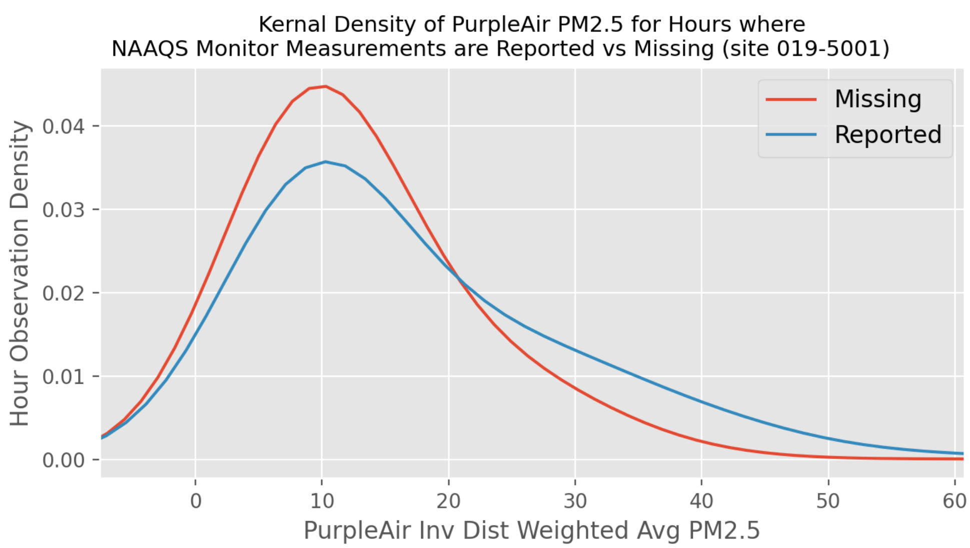

Figure 49: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 5001 in county 019 (FIPS code).

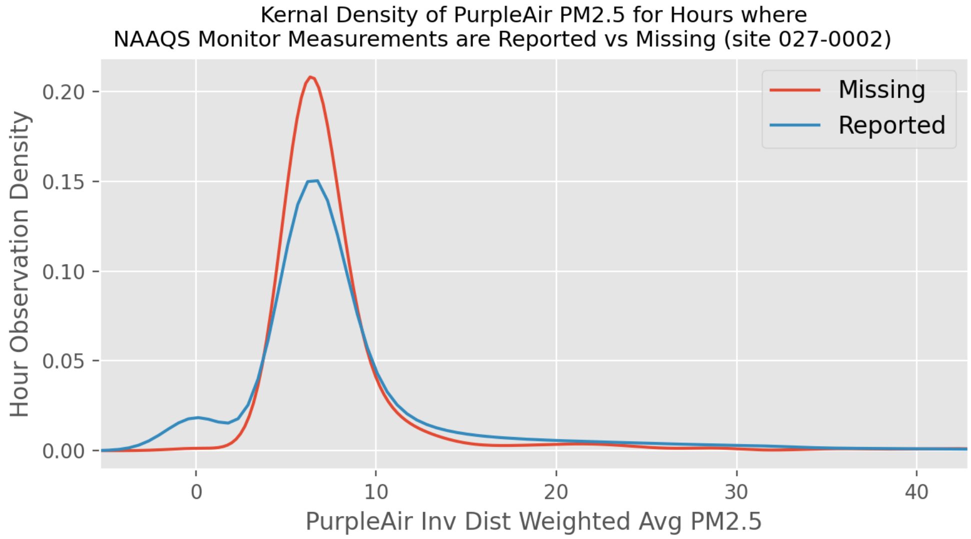

Figure 50: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 0002 in county 027 (FIPS code).

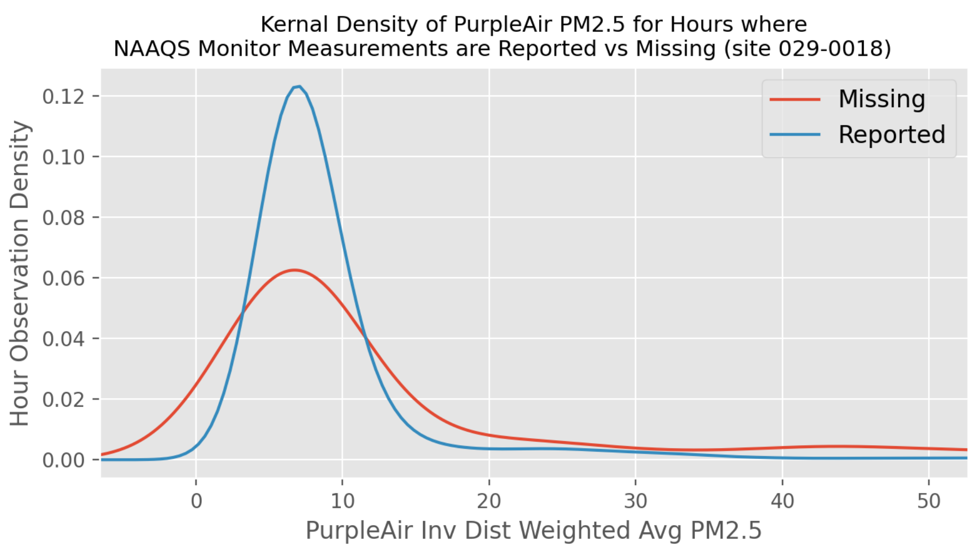

Figure 51: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 0018 in county 029 (FIPS code).

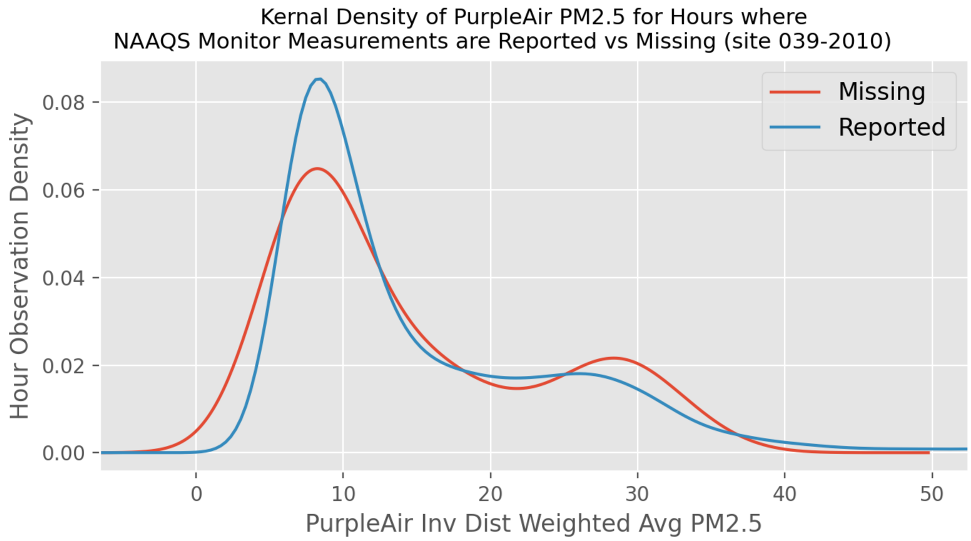

Figure 52: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 2010 in county 039 (FIPS code).

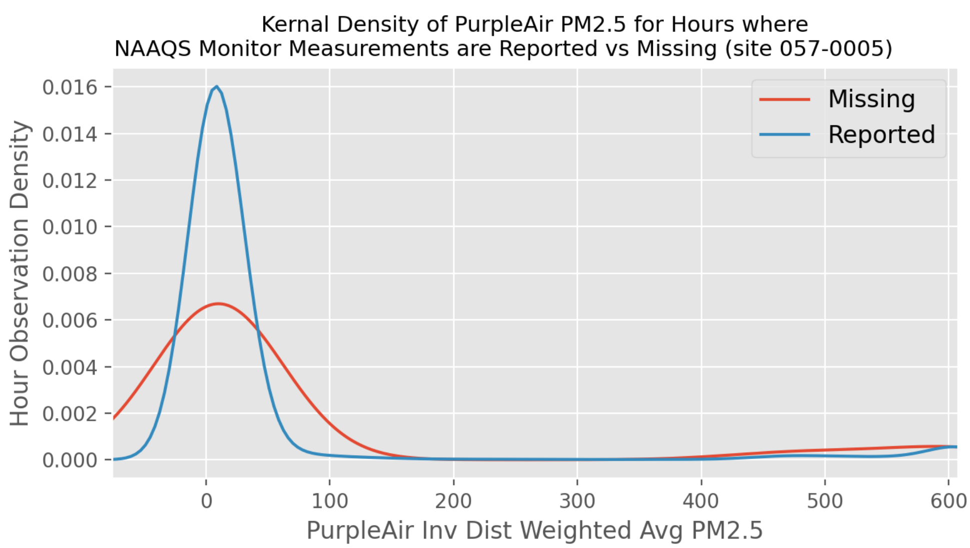

Figure 53: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 0005 in county 057 (FIPS code).

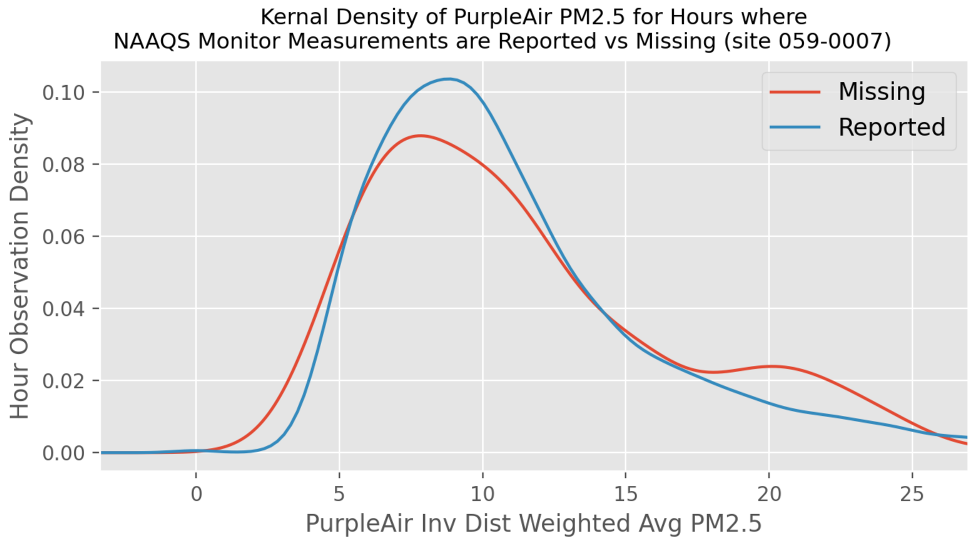

Figure 54: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 0007 in county 059 (FIPS code).

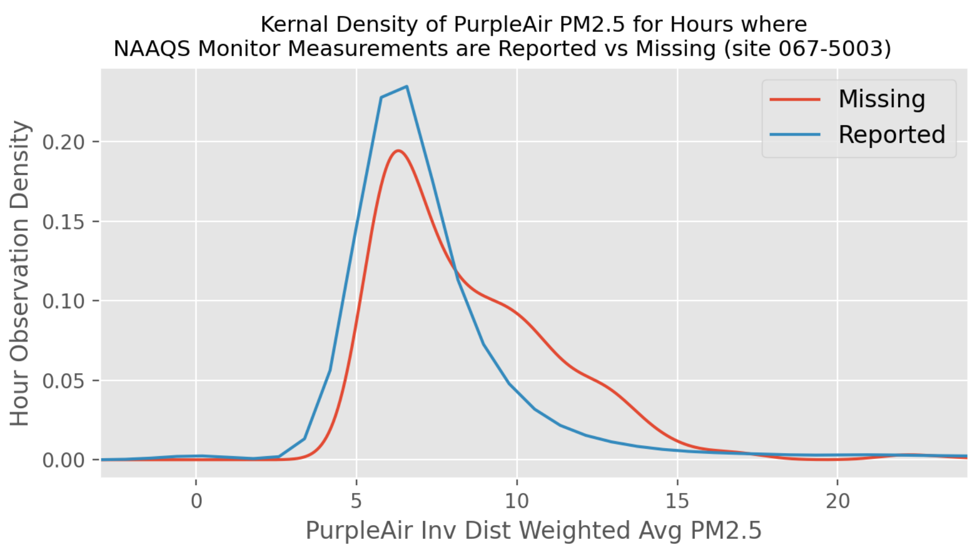

Figure 55: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 5003 in county 067 (FIPS code).

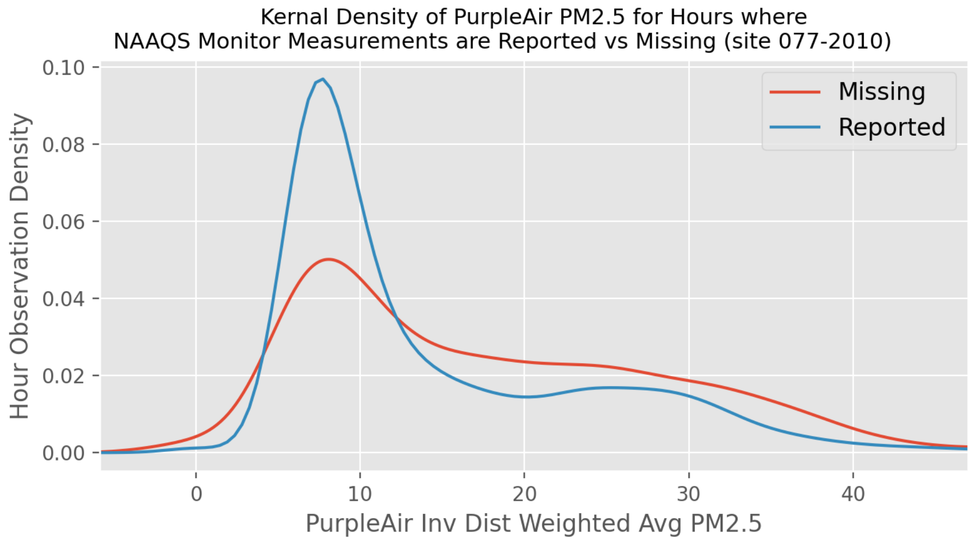

Figure 56: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 2010 in county 077 (FIPS code).

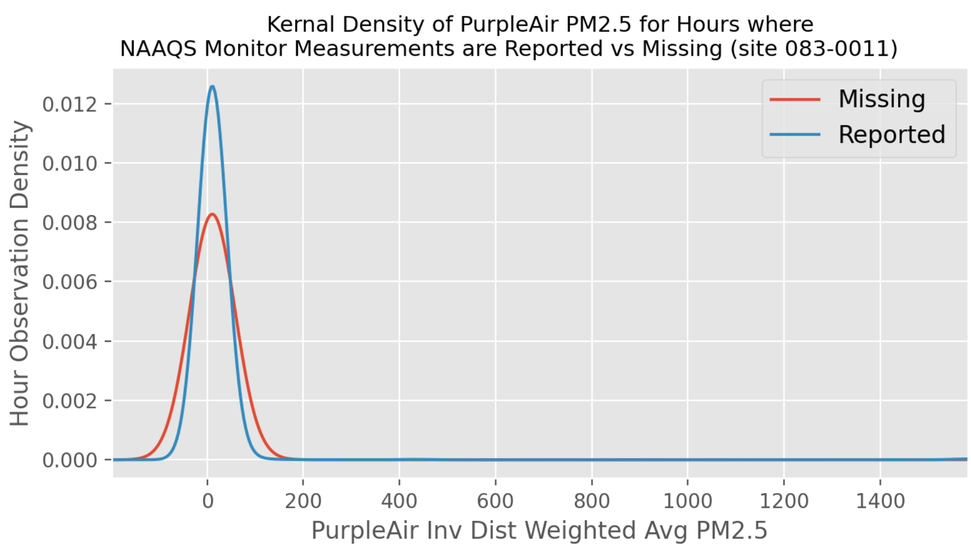

Figure 57: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 0011 in county 083 (FIPS code).

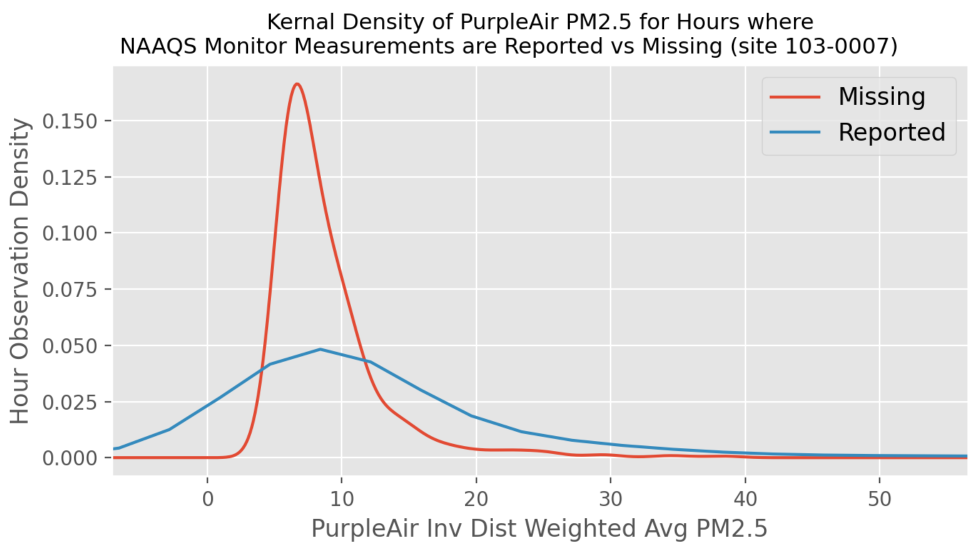

Figure 58: Comparison of PM2.5 concentration densities for two sets of hours: reported (blue) and missing (red) hourly observations of the NAAQS monitor. Both densities use the hourly PurpleAir PM2.5 concentration estimates for this site, calculated using the IDW average of PurpleAir sensors within 5 miles of the NAAQS monitor location. This monitor is at site 0007 in county 103 (FIPS code).