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Ambient Air Quality Analysis: Scotia Lumbermill Biomass Plant

Cal Poly Humboldt – Data Science Club (Fall 2025)
In association with Redwood Coast Energy Authority (RCEA)
December 15th, 2025

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1. Introduction

The Scotia Biomass Plant in Humboldt County generates renewable energy by combusting sawmill byproducts, including wood chips, sawdust, and forest residues, to produce electricity and thermal energy for kiln operations. Although biomass energy is classified as renewable, combustion processes still release air pollutants such as fine particulate matter ($PM_{2.5}$), nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOCs). These emissions have potential implications for local air quality and public health, particularly in small rural communities where monitoring infrastructure is limited.

Biomass facilities are frequently located near rural towns, where population density is low and regulatory oversight is often less intensive than in urban areas. As a result, residents in these communities may experience disproportionate exposure to air pollutants. While proponents of biomass energy emphasize benefits such as waste reduction and wildfire risk mitigation, critics highlight concerns related to air quality, greenhouse gas emissions, and community health. The scientific and policy literature remains divided on the net environmental and health impacts of biomass energy systems.

In collaboration with the Redwood Coast Energy Authority (RCEA), the Cal Poly Humboldt Data Science Club conducted this analysis to evaluate whether emissions from the Scotia Biomass Plant are associated with measurable changes in local $PM_{2.5}$ concentrations. Specifically, this study examines how plant emissions interact with meteorological conditions particularly wind direction to influence air quality at nearby monitoring locations.

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2. Results: Emissions and Air Quality Trends

2.1 Time-Series Patterns in Emissions and PM2.5

Daily total NOx emissions from the Scotia Biomass Plant and daily maximum $PM_{2.5}$ concentrations recorded in 2024 are shown in Figure 1. Plant emissions remain relatively stable throughout most of the year, generally fluctuating between approximately 0.2 and 0.35 units, with brief reductions in February, July, and December that likely reflect scheduled maintenance or reduced operational activity.

In contrast, $PM_{2.5}$ concentrations exhibit substantially greater temporal variability. Levels are typically lower during spring and summer months and become more variable in the fall and winter, when atmospheric conditions such as temperature inversions and reduced boundary-layer mixing can trap pollutants near the surface. A pronounced $PM_{2.5}$ spike occurs in early November, exceeding 50 $\mu g/m^3$. During this period, total NOx emissions also increase modestly, suggesting elevated plant activity. However, the magnitude of the $PM_{2.5}$ spike exceeds what would be expected from changes in plant emissions alone, indicating that regional smoke transport or stagnant meteorological conditions likely contributed.

Overall, the time-series comparison shows that $PM_{2.5}$ concentrations do not consistently track plant emissions, implying that meteorology and background pollution play a dominant role in day-to-day air quality variability.

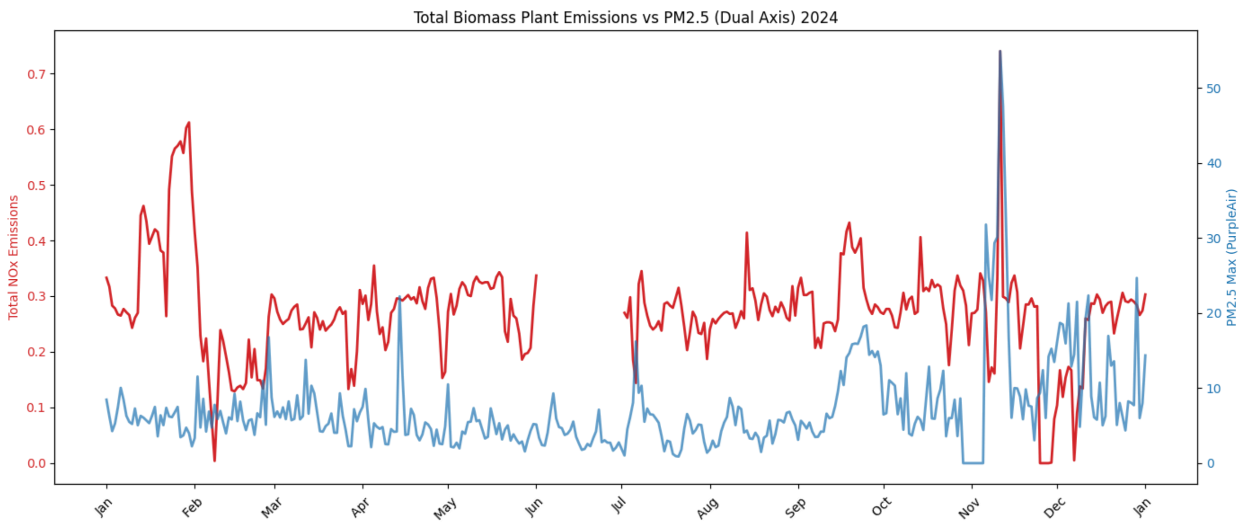

Figure 1. Daily total NOx emissions from the Scotia Biomass Plant and daily maximum PM2.5 concentrations in Scotia, California (2024).

2.2 Correlation Between Emissions and PM2.5

To quantify the relationship between plant emissions and particulate concentrations, correlations were calculated between total daily NOx emissions and both daily minimum and maximum $PM_{2.5}$ values. The correlation with minimum $PM_{2.5}$ was 0.055, while the correlation with maximum $PM_{2.5}$ was 0.018. These values indicate extremely weak linear relationships, suggesting that emissions alone are poor predictors of $PM_{2.5}$ concentrations when all days are analyzed together.

This outcome is consistent with expectations, as $PM_{2.5}$ levels are influenced by a combination of local emissions, regional pollution transport, meteorological dispersion, and secondary particle formation. Without accounting for atmospheric conditions, particularly wind direction the influence of the biomass plant is difficult to detect using simple correlations.

2.3 Role of Wind Direction and Atmospheric Transport

Because the PurpleAir monitoring sensors used in this study are located north of the Scotia Biomass Plant, emissions are most likely to affect measured $PM_{2.5}$ concentrations when winds blow from the south toward the north. To provide context for the wind-conditioned analysis, the distribution of wind directions over the study period is shown in Figure 2. Winds are predominantly northwesterly, while southerly winds occur less frequently. This indicates that downwind transport conditions represent a subset of observation days rather than the dominant wind regime, reducing the likelihood that elevated $PM_{2.5}$ under southerly winds reflects background conditions alone. When the dataset is restricted to these downwind conditions, average $PM_{2.5}$ concentrations are approximately 56 percent higher than on days with other wind directions. This finding highlights the importance of atmospheric transport in determining when plant emissions become detectable at the monitoring site.

These results demonstrate that the relationship between emissions and air quality is conditional rather than constant. The plant's contribution to local $PM_{2.5}$ levels becomes evident primarily when meteorological conditions favor pollutant transport toward the sensor, while on other days background pollution and dispersion dominate observed concentrations.

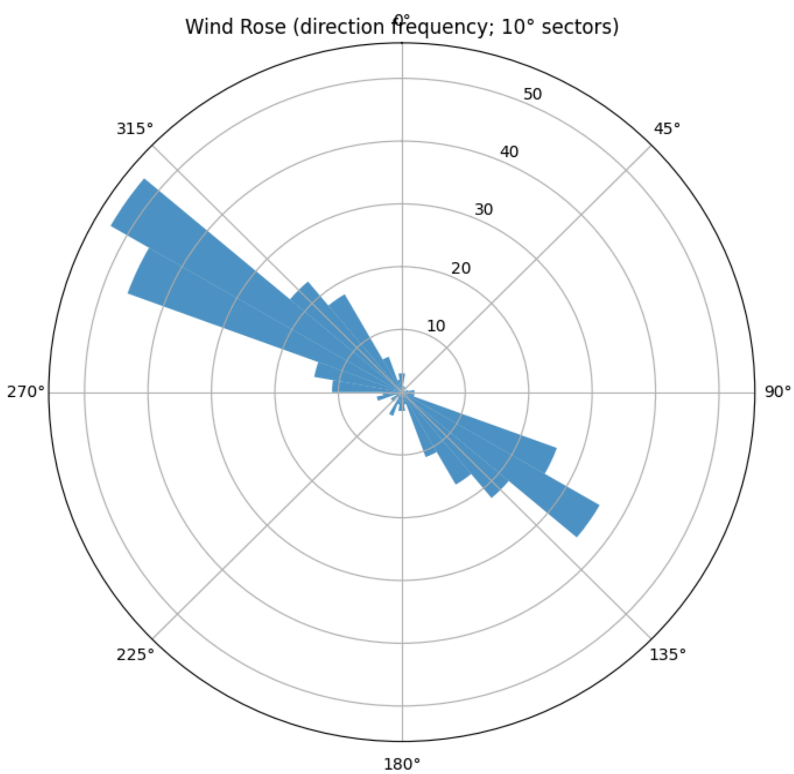

Figure 2. Wind direction frequency over the study period shown as a wind rose with 10° sectors. The monitoring site is located north of the Scotia Biomass Plant; southerly winds represent conditions under which plant emissions would be transported toward the sensor.

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3. Wind-Conditioned PM2.5 Analysis

Before grouping observations into downwind and non-downwind categories, $PM_{2.5}$ concentrations were examined as a function of wind direction using directional bins. Figure 3 shows median daily maximum $PM_{2.5}$ concentrations binned in 15° increments, along with the interquartile range. $PM_{2.5}$ levels exhibit clear directional structure, with elevated medians and increased variability observed within the southerly sector (approximately 135°–225°), corresponding to conditions under which emissions from the biomass plant would be transported toward the monitoring site.

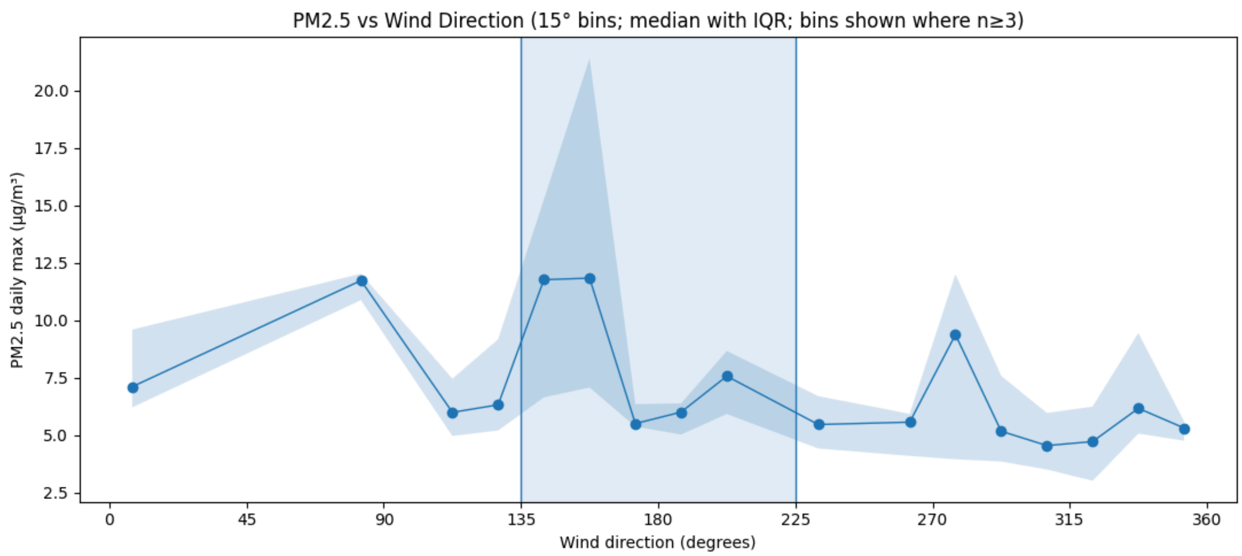
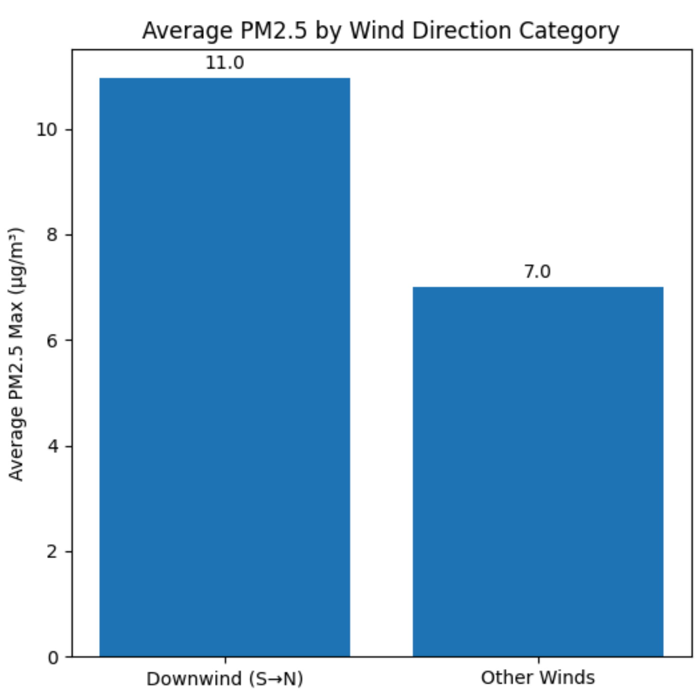


Figure 3. Median daily maximum $PM_{2.5}$ concentrations by wind direction (15° bins), with interquartile range shown. Shaded region denotes the southerly sector used to define downwind transport conditions. Bins shown where n ≥ 3.

To further evaluate the influence of wind direction, $PM_{2.5}$ concentrations were explicitly compared across downwind and non-downwind conditions. Average $PM_{2.5}$ on downwind days was 10.95 µg/m³, compared to 6.99 µg/m³ on non-downwind days, representing an approximate 56 percent increase when emissions were transported toward the monitoring site (Figure 2).



This directional pattern strengthens the interpretation that the biomass plant contributes to elevated particulate concentrations under specific atmospheric conditions. The consistency between wind direction and increased $PM_{2.5}$ levels also supports the physical validity of the PurpleAir measurements.

Figure 4. Average PM2.5 concentrations in Rio Dell under downwind (southerly) and non-downwind wind conditions.

3.1 Seasonal Context and Potential Confounders

A closer examination of the data reveals that many downwind observations occur during winter months. This introduces potential confounding factors, as residential wood burning, increased heating demand, and more frequent atmospheric inversions can elevate $PM_{2.5}$ levels during winter independent of plant operations. As a result, elevated particulate concentrations during downwind periods cannot be attributed solely to biomass plant emissions.

Seasonal patterns in plant activity provide additional context. The summer months, which exhibit lower $PM_{2.5}$ concentrations, also correspond to reduced plant operations. This overlap complicates causal interpretation, as lower emissions and more favorable dispersion conditions occur simultaneously.

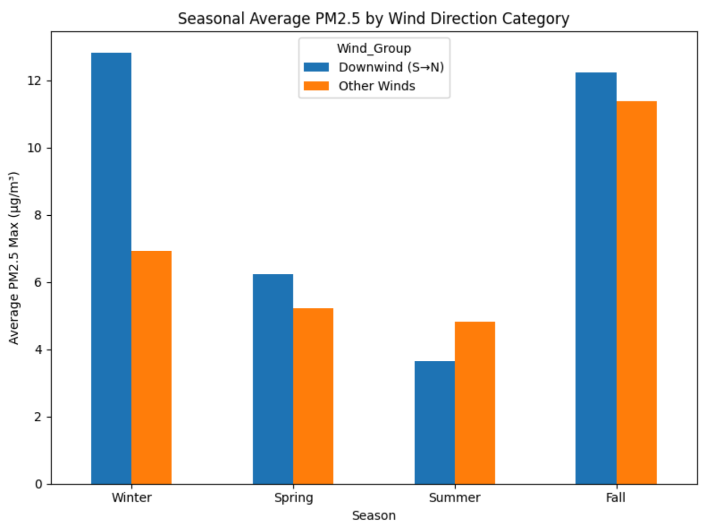


Figure 5. Seasonal comparison of PM2.5 concentrations by wind direction.

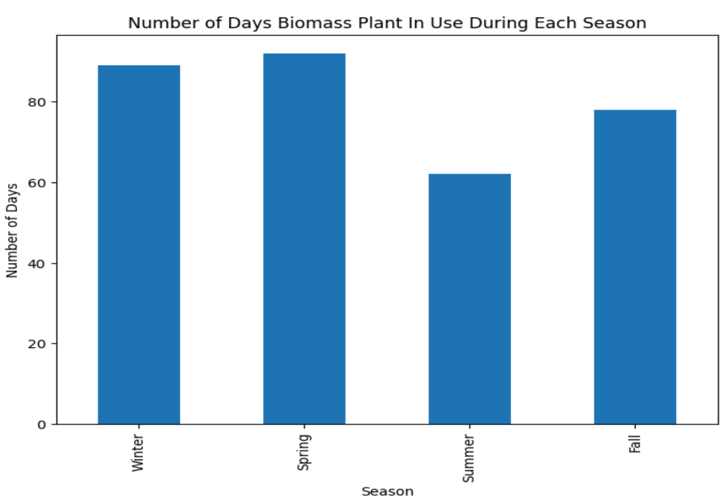


Figure 6. Number of operational days by season for the Scotia Biomass Plant.

3. Statistical Analysis

To formally assess the influence of wind direction and plant emissions on $PM_{2.5}$ concentrations, several statistical tests were conducted. The dataset included 328 valid observation days, of which 51 were classified as downwind days and 277 as non-downwind days.

Average daily maximum $PM_{2.5}$ on downwind days (10.95 µg/m³) was substantially higher than on non-downwind days (7.00 µg/m³). A Welch's t-test, which accounts for unequal sample sizes and variances, confirms that this difference is statistically significant ($t = 3.904$, $p = 0.0002$). The effect size, measured using Cohen's d, was 0.662, indicating a moderate to large practical effect.

Correlation analysis reinforces the importance of meteorological context. Across all days, the correlation between total NOx emissions and daily maximum $PM_{2.5}$ was effectively zero ($r = 0.018$). When restricted to downwind days only, the correlation became moderately negative ($r = –0.313$). This counterintuitive result reflects the complexity of $PM_{2.5}$ dynamics, as wintertime residential emissions and stagnant atmospheric conditions can elevate particulate levels even when plant emissions remain stable or decline.

Linear regression models were used to further isolate these effects. A full-year model including downwind conditions and total NOx emissions shows that downwind transport is a statistically significant predictor of $PM_{2.5}$ concentrations (coefficient = 4.29, $p < 0.001$), while total NOx emissions are not ($p = 0.15$). Although the model explains a modest portion of overall variability ($R^2 = 0.061$), the consistent significance of wind direction highlights its central role.

A winter-only regression provides a robustness check. Even during this season, downwind conditions remain strongly associated with higher $PM_{2.5}$ concentrations (coefficient = 5.37, $p < 0.001$), while NOx emissions remain non-significant. This indicates that elevated $PM_{2.5}$ levels during downwind periods cannot be explained solely by seasonal background pollution.

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5. Conclusion

This analysis indicates that the influence of the Scotia Biomass Plant on local air quality varies with atmospheric conditions rather than occurring uniformly across time. Plant emissions do not consistently elevate $PM_{2.5}$ concentrations across all days; instead, their influence becomes detectable primarily when wind direction and atmospheric conditions favor transport toward nearby monitoring sites.

Wind direction emerges as a stronger determinant of observed $PM_{2.5}$ levels than total daily emissions, underscoring the importance of incorporating meteorological context into air quality assessments. These findings highlight the limitations of relying on annual averages or simple correlations when evaluating localized environmental impacts, particularly in rural communities.

For policymakers and monitoring agencies, the results suggest that targeted monitoring strategies, such as sensor placement informed by prevailing wind patterns can improve the detection of localized emission impacts. More broadly, this study illustrates the value of combining emissions data with meteorological analysis to better understand the real-world air quality implications of renewable energy infrastructure.