Forecasting the Health Impacts of Wildfire Smoke in Birmingham

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1. Introduction

The increasing frequency and intensity of wildfires due to climate change have become significant environmental and public health concerns. Smoke from these wildfires can travel vast distances, affecting air quality in urban areas far removed from the fires themselves. Birmingham, Alabama, is one such city that, despite not being in a traditionally fire-prone region, experiences the impacts of smoke from distant wildfires.

Exposure to wildfire smoke is associated with a range of adverse health effects, particularly respiratory diseases. Particulate matter and other pollutants found in smoke can exacerbate existing respiratory conditions and contribute to increased morbidity and mortality rates. According to the Environmental Protection Agency (EPA), particulate pollution can cause and aggravate respiratory illnesses such as asthma and bronchitis (EPA, n.d.). Moreover, recent research indicates that wildfire smoke has a more significant impact on respiratory health than particulate matter from other sources (Aguilera et al., 2021).

Understanding the relationship between wildfire smoke exposure and respiratory health outcomes is crucial for city officials, public health agencies, and residents of Birmingham. By analyzing this relationship, stakeholders can develop targeted interventions to mitigate health risks associated with smoke exposure. This study aims to quantify the impact of wildfire smoke on respiratory disease mortality rates in Birmingham by developing a Smoke Index based on wildfire data and correlating it with mortality data from reputable health databases.

The findings of this analysis have practical implications for public health planning and policymaking. Identifying periods of high smoke exposure and associated increases in respiratory mortality can inform the implementation of measures such as enhanced air quality alert systems, public health advisories, and allocation of resources for healthcare services. Additionally, understanding these impacts can guide long-term strategies to enhance community resilience against environmental threats exacerbated by climate change.

By providing evidence-based insights into the health effects of wildfire smoke, this study supports proactive decision-making to protect vulnerable populations in Birmingham. It underscores the importance of addressing environmental health challenges through informed policies and community engagement, ultimately contributing to a healthier and more resilient urban environment.

2. Background and Related Work

2.1 Health Impacts of Wildfire Smoke

Wildfire smoke is a complex mixture of pollutants, including fine particulate matter ($PM_{2.5}$), carbon monoxide, and volatile organic compounds. Exposure to these pollutants has been linked to various adverse health outcomes, particularly affecting the respiratory and cardiovascular systems. Studies have shown that inhalation of $PM_{2.5}$ from wildfire smoke can exacerbate conditions such as asthma and chronic obstructive pulmonary disease (COPD), leading to increased hospital admissions and mortality rates. [1]

Recent research has also identified associations between long-term exposure to wildfire smoke and increased risks of lung cancer and brain tumors, highlighting the potential for severe long-term health consequences. [2]

2.2 Urban Air Quality and Wildfire Smoke

Urban areas, even those distant from wildfire sources, are not immune to the effects of wildfire smoke. Studies have demonstrated that smoke can travel vast distances, degrading air quality in cities and leading to exceedances of health-based air quality standards. [3]

This phenomenon has been observed across the United States, where wildfire smoke has reversed decades of improvements in air quality by increasing levels of $PM_{2.5}$ and ozone[4].

In Birmingham, Alabama, the impact of transported wildfire smoke on local air quality has become a growing concern. The city's proximity to regions prone to wildfires, drought predictions, combined with prevailing wind patterns, can result in significant smoke intrusions, adversely affecting air quality and public health.

2.3 Existing Models and Data Sources

Various models have been developed to assess the impact of wildfire smoke on air quality and health outcomes. These models often incorporate data on fire emissions, atmospheric

transport, and chemical transformations to predict pollutant concentrations. For instance, the BlueSky Modeling Framework [5] integrates fire information with meteorological data to estimate smoke dispersion and concentrations of $PM_{2.5}$.

In this study, we utilized Meta's Prophet model [6], a time-series forecasting tool, to project both the Smoke Index and respiratory mortality rates. Prophet is particularly suited for time-series data with strong trends and seasonal components, although seasonality was excluded in this case due to annual data aggregation. Its flexibility in handling missing data, robust trend fitting, and ability to incorporate external regressors (e.g., the Smoke Index as a predictor for mortality) made it an ideal choice for this analysis. By leveraging Prophet, we were able to model historical trends in smoke exposure and mortality and forecast their trajectories through 2050, providing valuable insights into potential future health impacts.

Additionally, this study relied on the Centers for Disease Control and Prevention's Compressed Mortality File (CMF) [7][8] to obtain respiratory mortality data for Jefferson County, Alabama. The CMF provides comprehensive mortality statistics, including cause-specific death counts and rates, which are essential for analyzing health outcomes associated with environmental exposures. The integration of CMF data with the Smoke Index allowed for a robust analysis of the relationship between wildfire smoke and respiratory health outcomes in Birmingham.

2.4 Hypotheses

Based on the existing literature and the context of Birmingham, this study posits the following hypotheses:

1. **Increased smoke exposure correlates with higher respiratory mortality**: Elevated levels of wildfire smoke exposure are associated with increased mortality rates from respiratory diseases in Birmingham.
2. **Vulnerable populations are disproportionately affected**: Certain demographic groups, such as the elderly and individuals with pre-existing health conditions, experience higher mortality rates during periods of increased smoke exposure.
3. **Temporal lag between exposure and health outcomes**: There is a measurable time lag between peak smoke exposure events and subsequent increases in respiratory mortality rates.

By investigating these hypotheses, the study aims to enhance understanding of the health impacts of wildfire smoke in urban settings and inform public health interventions and

policy decisions.

3. Methodology

This study investigates the impact of wildfire smoke on respiratory mortality rates in Birmingham, Alabama, by creating and analyzing a Smoke Index, integrating mortality data, and employing statistical models to uncover correlations and project future trends. The methodology reflects a balance between robust data processing and interpretability, aiming to provide actionable insights for public health interventions.

3.1 Analytical Approach

1. Development of the Smoke Index

To quantify the impact of wildfire smoke on Birmingham, a Smoke Index was developed using wildfire data, incorporating the following factors:

- **Area Burned**: Total area affected by fires.
- **Proximity to Birmingham**: Weighted by inverse squared distance to account for the dispersion of smoke over distance.
- **Type of Fire**: Different weights were assigned to account for variability in smoke production based on fire type. (1 for wildfire and 0.6 for prescribed fire)

The formula used for the Smoke Index was:

$$Smoke\ Index = \frac{Area\ Burned \times \alpha}{Distance\ from\ City^2}$$

This index served as the primary explanatory variable in subsequent models.

2. Smoke Index Projection

The historical Smoke Index was projected up to 2050 using Meta's Prophet model [6], a time-series forecasting tool. Since the data was aggregated yearly, seasonality was not included in the model. The projection provided insights into the long-term trends of wildfire smoke exposure for Birmingham under the assumption of continued wildfire severity increases.

3. Mortality Data Integration and Exploration

Respiratory mortality data was obtained from the CDC's Compressed Mortality File (CMF) for Jefferson County, which encompasses Birmingham. The analysis included:

- Using raw mortality rates, including suppressed values (counts below ten), with the intent to aggregate these values in later analyses.
- Performing exploratory data analysis (EDA) to identify trends, patterns, and anomalies in the data.

Separate mortality rates for male and female populations were also analyzed to uncover potential gender-specific differences in the impact of smoke exposure.

4. Predictive Modeling of Mortality

Two models were fitted using Meta's Prophet, with the Smoke Index as an external regressor:

- **Overall Mortality**: Predicted respiratory mortality rates using historical smoke and mortality data. Future mortality rates were forecasted using the projected Smoke Index.
- **Gender-Specific Mortality**: Separate models were developed for male and female mortality rates, revealing that female respiratory mortality was more significantly affected by smoke exposure compared to males.

The methodology ensured that the relationship between smoke exposure and respiratory mortality was quantified and forecasted effectively, providing a granular understanding of how smoke impacts different demographic groups.

3.2 Human-Centered Considerations

1. **Data Privacy**: While suppressed mortality values were included in the analysis for aggregation purposes, results were handled and reported in a manner consistent with CDC confidentiality guidelines.
2. **Equity Focus**: Gender-specific analyses were conducted to understand disparities and highlight vulnerable populations disproportionately affected by wildfire smoke.

4. Findings

The findings of this analysis highlight the significant relationship between wildfire smoke exposure and respiratory mortality rates in Birmingham, Alabama. Through exploratory data analysis, statistical modeling, and forecasting, key insights were derived, offering a deeper understanding of current trends and future risks.

4.1 Smoke Index Trends and Projections

The Smoke Index, calculated using wildfire area, distance, and type, shows an upward trend over the years. This trend reflects the increasing frequency and severity of wildfires, likely exacerbated by climate change. The projection of the Smoke Index using Meta's Prophet model suggests a continued rise in smoke exposure for Birmingham through 2050, with no indication of a plateau under current conditions.

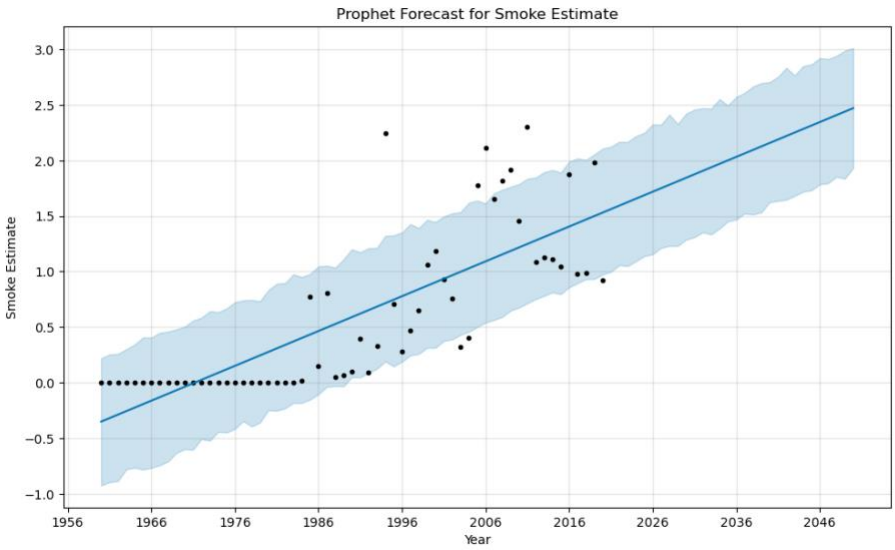

Figure 1

4.2 Respiratory Mortality Trends

Exploratory analysis of the respiratory mortality data from the CDC revealed a steady decline in mortality rates in across decades, likely due to advancements in healthcare and reduced smoking rates. The detrended data highlights correlation between mortality and smoke related features in the correlation matrix below.

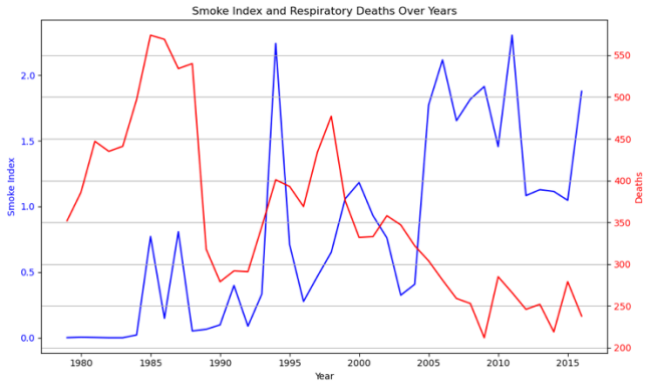

Figure 2

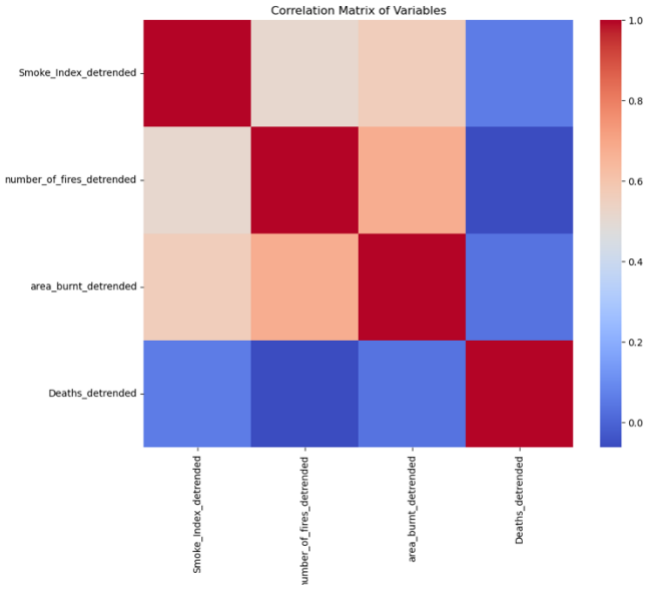

Figure 3

4.2 Relationship Between Smoke and Mortality

Prophet models incorporating the Smoke Index as an external regressor revealed a statistically significant positive relationship between smoke exposure and respiratory mortality. Forecasts predict an increase in mortality rates through 2050 if smoke exposure continues to rise.

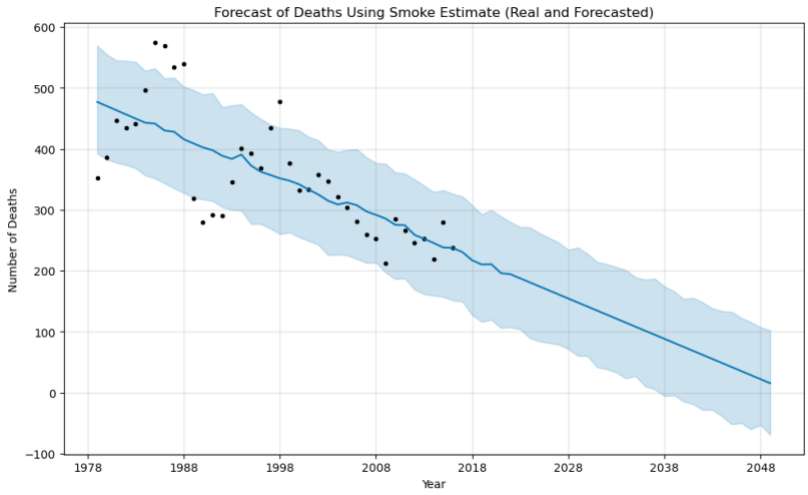

Figure 4

4.4 Gender-Specific Impacts

Separate models for male and female mortality rates uncovered notable differences:

- **Male Mortality**: While smoke exposure influenced male respiratory mortality, the effect size was smaller compared to females.
- **Female Mortality**: A stronger correlation between smoke exposure and respiratory mortality was observed for females, indicating greater vulnerability to smoke-related health impacts.

Gender-specific analyses emphasize the importance of targeted public health interventions to address disparities.

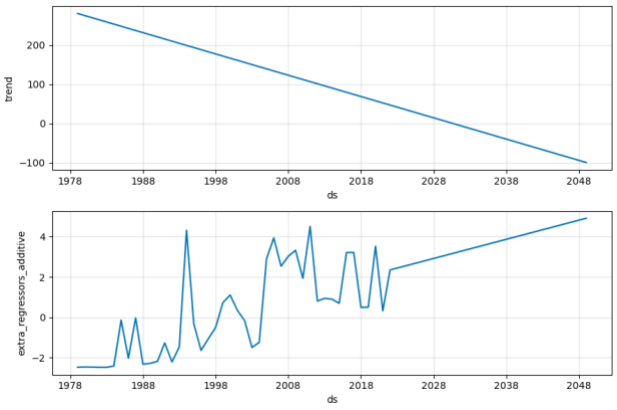

Figure 5: Breakdown of components of model predicting. Male Mortality with smoke as regressor

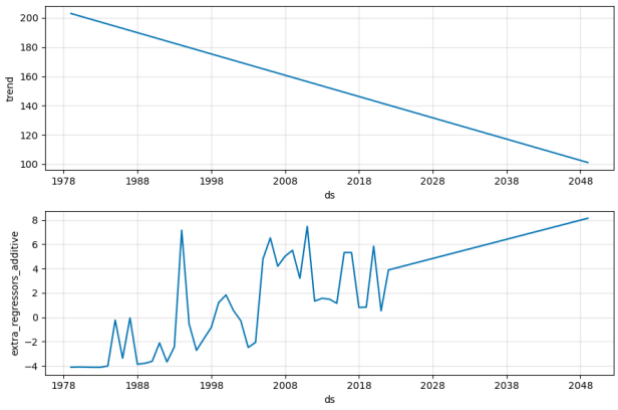

Figure 6: Breakdown of components of model predicting Female Mortality with smoke as regressor

5. Discussion and Implications

The results of this analysis provide valuable insights into the complex relationship between wildfire smoke exposure and respiratory mortality in Birmingham, Alabama. While the general trend indicates that respiratory mortality rates are expected to decrease over time—likely due to advancements in healthcare and other socio-environmental improvements—smoke exposure remains a critical risk factor. Specifically, the findings reveal that:

1. **Smoke Increases Mortality Rates**: Wildfire smoke significantly contributes to respiratory mortality, counteracting the overall downward trend. This highlights the

pressing need to address smoke-related health risks as part of long-term public health planning.

2. **Women Are Disproportionately Affected**: A new and important finding is the greater sensitivity of women to smoke exposure, with mortality rates for females showing a stronger correlation with smoke events compared to males. This disparity underscores the need for gender-specific health interventions and policies.

5.1 Implications for Jefferson County

1. Addressing the Health Impact of Smoke

Given the dual realities of a declining overall mortality trend and the acute risk posed by smoke exposure, Jefferson County should prioritize the following actions:

- **Strengthening Health Surveillance**: Enhance real-time monitoring of respiratory disease trends and air quality to identify periods of elevated risk. This includes creating localized smoke exposure maps that consider wildfire events and wind patterns affecting Birmingham.
- **Developing Gender-Sensitive Health Policies**: The greater impact of smoke on women necessitates targeted interventions. These could include:
    - Increasing access to respiratory health resources for women, particularly during peak smoke periods.
    - Conducting community workshops focusing on women's health and smoke mitigation strategies.
- **Promoting Personal Protective Measures**: Encourage residents to adopt protective measures during smoke events, such as using HEPA air purifiers and wearing masks, particularly for vulnerable groups like women, the elderly, and those with pre-existing conditions.

2. Long-Term Policy Interventions

To mitigate the projected health risks associated with increasing wildfire smoke exposure, Jefferson County must implement forward-looking strategies:

- **Investing in Air Quality Infrastructure**:
    - Deploy air quality sensors across the county to better track and forecast smoke events.

    - Establish indoor "clean air shelters" for community use during periods of poor air quality.

- **Incorporating Findings into Public Health Planning**:
    - Use this study's results to prioritize respiratory health in public health budgets and resource allocation.
    - Partner with healthcare providers to offer specialized services for conditions exacerbated by smoke, with an emphasis on high-risk groups.
- **Educational Campaigns for Smoke Resilience**:
    - Launch public awareness campaigns about the health risks of wildfire smoke and practical steps for mitigation.
    - Emphasize the greater impact on women to foster community-level support for gender-sensitive measures.

5.2 Human-Centered Reflections

This study emphasizes equity by identifying the disproportionate impact of wildfire smoke on women and recommending gender-sensitive public health policies to address these disparities. Clear visualizations and straightforward interpretations ensure the results are accessible to a broad range of stakeholders, including policymakers, healthcare professionals, and residents. Ethical considerations were also paramount, with suppressed mortality values aggregated responsibly to maintain confidentiality while maximizing the robustness of findings.

The urgency of the findings demands immediate action, as Jefferson County faces a rising risk of smoke exposure. A concrete plan should be implemented within 3–5 years, combining immediate steps like public awareness campaigns with long-term strategies such as improved air quality infrastructure and tailored health policies. Finally, this study’s insights extend beyond Birmingham, serving as a model for other urban communities to adopt evidence-based, inclusive, and proactive approaches to address the growing health threats posed by wildfire smoke.

6. Limitations

While this study provides valuable insights into the relationship between wildfire smoke and respiratory mortality, several limitations must be acknowledged. These limitations highlight potential biases, uncertainties, and areas for improvement in future research.

- **Data Limitations:** The analysis used raw mortality data, including suppressed values and non-age-adjusted rates, which may introduce bias and limit the robustness of demographic-specific insights. Additionally, confounding variables like socioeconomic factors or seasonal illnesses were not accounted for, potentially affecting the observed relationships.
- **Modeling Simplifications:** The Smoke Index relied on simplified assumptions, omitting meteorological factors like wind and humidity, which influence smoke dispersion. Projections of smoke exposure and mortality assume static historical trends, which may not hold under future policy or climate changes.
- **Generalizability:** The findings are specific to Birmingham and its surrounding context, with factors such as population demographics and air quality infrastructure varying widely across regions. As a result, the analysis may have limited applicability to other urban areas facing similar challenges.

These limitations, while notable, do not undermine the significance of the study's findings. Instead, they offer valuable direction for future research and underscore the complexity of analyzing environmental health impacts in urban settings.

7. Conclusion

This study investigated the relationship between wildfire smoke exposure and respiratory mortality in Birmingham, Alabama. The findings confirm that while overall respiratory mortality rates are expected to decline due to healthcare advancements, wildfire smoke remains a significant risk factor that increases mortality. Importantly, the analysis revealed that women are disproportionately affected by smoke exposure, highlighting the need for gender-sensitive interventions. Projections indicate that the Smoke Index will continue to rise through 2050, underscoring the urgency of proactive measures.

By uncovering these insights, this study contributes to human-centered data science through its focus on equity, actionable findings, and ethical data practices. The results provide a foundation for Jefferson County to implement targeted public health policies and interventions, ensuring a healthier and more resilient community. These insights can also inform strategies in other cities facing similar environmental challenges.

8. References

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9. Data Sources

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