Wildfire Impacts in the Denver Metro Region: A Human-Centered Data Analysis of Economic and Environmental Challenges

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Introduction

Wildfires in Colorado

Wildfires in Colorado have become more common and severe over the past 20 years, according to the Colorado Department of Public Safety. The Colorado State Forest Service says this increase is due to climate change, long droughts, and forest management challenges. All of Colorado's 20 largest wildfires happened after 2001. In the last 13 years, there were 16 major fires, and 9 of them occurred in just the past 3 years.

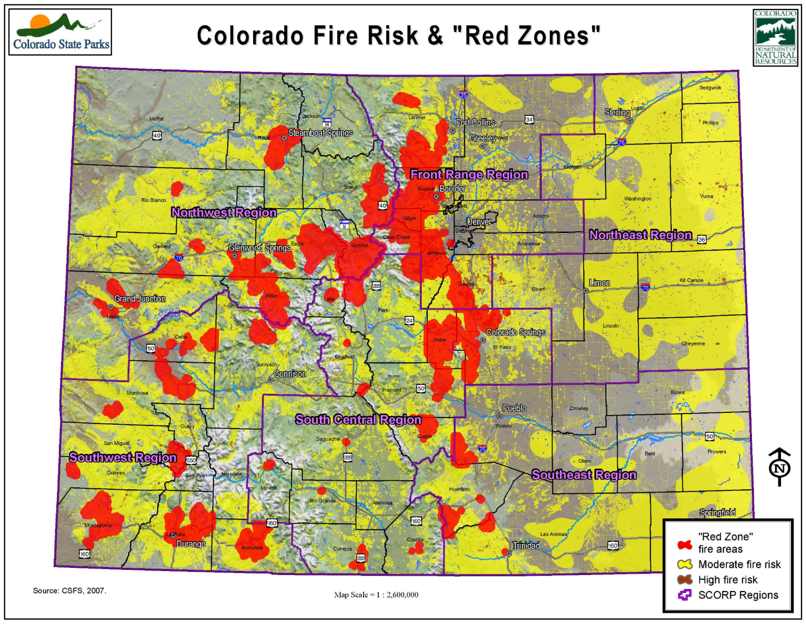


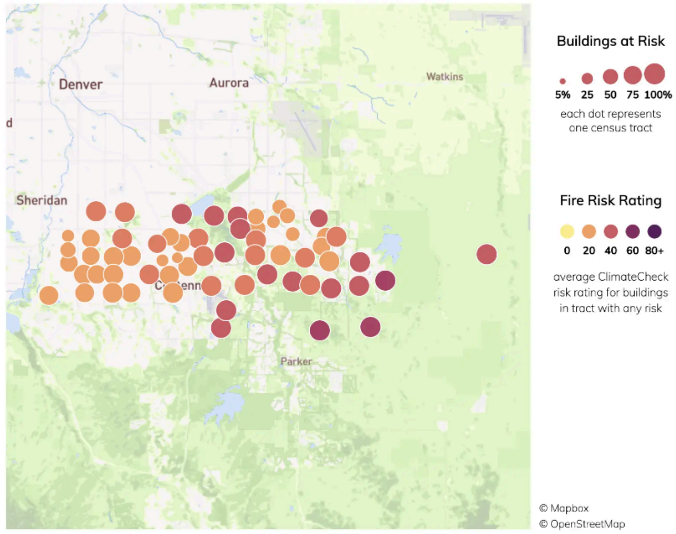
Figure 1: The map above illustrates fire risk across the state, with "red zones" marking areas that are certain to face wildfire activity at some point. More than 1 million Colorado residents now live in these red zones, while millions more reside in areas with moderate risk.

According to an article by the Nature Conservancy The Cameron Peak Fire in 2020 burned over 208,000 acres and damaged 470 structures, making it the largest wildfire in Colorado's history. Wildfires are also destroying more homes, like the Marshall Fire in 2021, which burned over 1,000 homes. The economic damage from wildfires in Colorado is huge. According to the same source, the Buffalo Creek Fire (1996) and the Hayman Fire (2002) together caused $27 million in damages to water supplies [2]. These damages affect watersheds that are critical for irrigating crops and supporting Colorado's agriculture industry.

The smoke from wildfires harms public health. According to this article, titled "What are the costs of wildfire? CSU resource economics expert answers", it has led to more hospital visits for asthma, breathing problems, and heart issues. Vulnerable groups like children and older adults are the most affected. Colorado's growing population increases the number of people at risk. In 2021, the U.S. The Census Bureau reported that about 5.8 million people lived in Colorado, and many were in wildfire-prone areas.

Wildfires in the Centennial and Denver Metro Area

The Denver-Aurora-Lakewood metropolitan area, including Centennial, faces increasing wildfire risks. Centennial is in Arapahoe County and has about 55,000 residents. Many of these residents live near wildland areas, which are especially at risk for fires. Colorado's population continues to grow. According to an article by Axios Denver, between July 2020 and July 2023, the Denver-Aurora-Centennial metro area added over 35,000 residents, growing by 1.2%. This population growth means more people are exposed to wildfire risks.



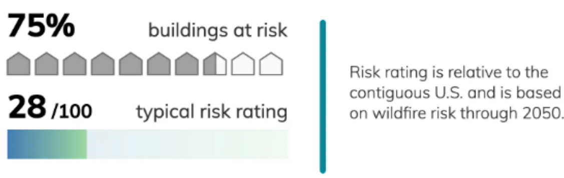


Figure 2(a) and Figure 2(b): Out of 84 census tracts in Centennial, CO, 74 have over a quarter of buildings at high fire risk, and 67 have more than half of buildings at high risk. Property owners can take steps to reduce their wildfire risk. Fire risk depends on how close buildings are to vegetation. Urban areas with dense development have a much lower risk compared to places near wildland. Climate change makes wildfires more likely by creating hotter and drier conditions that help fires spread. ClimateCheck rates fire risk based on future weather predictions and U.S. Forest Service fire behavior models.

The Marshall Fire in December 2021 showed how suburban and urban communities near wildland areas are vulnerable. This fire burned more than 6,000 acres and destroyed almost 1,100 homes in Boulder County, part of the greater Denver metro area. Wildfires in this region cause $200–300 million in damages each year, according to a University of Colorado study. This does not include indirect losses like business closures, lower property values, and health costs.

Health issues from wildfire smoke are a big problem in this region. Studies show smoke increases respiratory problems, especially in children and older adults, because it contains fine particles that can harm health. Even when fires are far away, smoke can affect air quality in the Denver-Aurora-Lakewood area.

Wildfires also hurt the local economy. According to an article by Investopedia titled "How Fire Season Affects the Economy", the outdoor recreation industry, worth $374 billion in 2020 (1.8% of the U.S. GDP), suffers because tourists avoid areas affected by fires and smoke. Smoke exposure from wildfires can also lower earnings in affected communities by 0.04% for up to two years.

Economic Impacts

The most substantial economic impact of wildfires is on real estate values, estimated at $67.5 to $337.5 billion annually. This effect is particularly pronounced in fire-prone areas where insurance costs are skyrocketing or coverage is becoming unavailable. Property damage from wildfires is also significant, with 2020 alone seeing $21.9 billion in damages. The real estate sector's vulnerability is becoming increasingly apparent, especially in areas like California, where home insurance prices are rising dramatically and several insurers have stopped writing new policies. Wildfires have a complex effect on labor markets. While they may temporarily increase employment due to fire suppression efforts, they tend to make local labor markets less stable over time. A study by IMPLAN found that wildfires could cost 466,000 jobs and $89.6 billion in lost economic output for the U.S. This impact on employment and economic output highlights the far-reaching consequences of wildfires beyond immediate property damage. The U.S. outdoor recreation economy, valued at nearly

$374 billion in 2020, is particularly vulnerable to wildfire impacts. Tourists tend to avoid areas affected by smoke, leading to widespread economic consequences for hospitality, restaurant, and related industries. This effect on tourism can have long-lasting impacts on local economies, especially in regions heavily dependent on outdoor recreation and tourism. Wildfires lead to increased hospital visits for asthma, respiratory issues, and cardiovascular problems. Exposure to wildfire smoke has been associated with a wide range of negative health impacts, including asthma exacerbations and heart attacks. These health effects can have long-term economic consequences, adding to the overall burden on the healthcare system and impacting productivity.

Stakeholders

The primary stakeholders affected by wildfires include residents in wildfire-prone areas, particularly those in the wildland-urban interface (WUI), property owners and real estate investors, tourism and outdoor recreation businesses, insurance companies, local and state governments, health care providers and systems, and forestry and land management agencies. Each of these groups faces unique challenges and plays a crucial role in wildfire mitigation and response efforts.

Mitigation Importance

Mitigating wildfire risks is crucial for protecting human lives and health, preserving property and economic stability in affected regions, maintaining ecological balance and protecting wildlife habitats, reducing the enormous economic burden on local and national economies, and ensuring the sustainability of industries dependent on healthy forests and clean air. The urgency of this issue is underscored by projections that suggest wildfire suppression costs could increase by 42% to 84% by 2050, potentially reaching $3.9 billion annually.

Related Work

Wildfires cause serious economic problems that affect communities, businesses, and governments. They destroy homes, infrastructure, and natural resources, while also hurting local economies by forcing people out of work, reducing spending, and disrupting important services. Businesses face challenges like shutdowns, delays in supplies, and worker shortages, leading to big financial losses. Entire industries, like tourism and farming, can also suffer for a long time because of damaged ecosystems and fewer visitors.

Economic Impact of Wildfires in the United States

The study by Walls, Margaret A., and Matthew Wibbenmeyer focuses on the 1998 wildfires in Florida and the 2003 wildfires in San Diego County, California, which caused economic losses of $880 million and $2.45 billion, respectively. These wildfires caused more than just immediate damage to homes and firefighting costs. They disrupted tourism, damaged infrastructure, and reduced the benefits provided by ecosystems, all of which are important to local economies. People were forced to leave their homes, suffered emotional stress, and faced health problems due to poor air quality. Businesses struggled with interruptions and loss of workers, while governments had to spend large amounts of money on firefighting and recovery, often cutting funds from other important services. The study suggests solutions such as investing in wildfire prevention, managing land sustainably, using fire-resistant building materials, and creating programs to help communities recover economically.

The study by Diaz, John M. looks at how wildfires affect job growth in the western United States by analyzing data from counties and areas close to fire locations. At the county level, job growth temporarily increased due to construction work needed for rebuilding. However, industries like tourism, healthcare, and education saw declines because of fewer visitors and local disruptions. In areas closer to the fires, the impact on jobs was worse in the short term, but recovery usually happened within a year. These results show that wildfires affect communities in very different ways, with some experiencing bigger challenges right after the event. The study highlights the importance of helping communities recover by supporting businesses, offering job training, and focusing on construction job development to build resilience and ensure everyone can recover fairly.

The study by Wang, Daoping, et al. estimates the total cost of California's 2018 wildfires at $148.5 billion, which includes $27.7 billion in direct damage to property, $32.2 billion in health-related costs, and $88.6 billion in indirect losses. Most of these indirect losses, such as supply chain disruptions, happened outside California, showing that wildfires affect areas far from the actual fires. These disruptions caused problems for industries and communities that depend on affected supply chains. The study recommends policies to protect key industries, reduce health problems caused by wildfire pollution, and encourage collaboration between regions to manage wildfire risks. By focusing on these issues, decision-makers can better protect communities and reduce the widespread economic effects of future wildfires.

Economic Consequences of Wildfires in the Centennial and Colorado Region

The study by Sherriff, Rosemary L., et al., examines the evolving severity of wildfires in the montane forest zone of Colorado's Front Range, which includes Centennial, and its implications for land management. Over the years, 16% of the area has shifted from historically low-severity fires to a higher risk of crown fires, with most changes occurring in lower elevations. Historically, the region experienced mixed-severity fires, which included both low- and high-severity events, a pattern that persists today at higher elevations. This means thinning trees in these areas is unlikely to restore a low-severity fire regime or prevent severe wildfires. The study emphasizes that while recent large wildfires, as of 2014, are not unprecedented—similar events occurred historically under extreme weather conditions—the growing frequency of such conditions due to climate change is intensifying wildfire risks. This worsening trend not only threatens ecosystems but also poses significant challenges to communities in the region. Although the study does not directly address social impacts, it underscores the urgent need for adaptive management strategies to mitigate wildfire risks and protect both the environment and human well-being.

Wildfires in Colorado significantly threaten air quality, both indoors and outdoors, with severe public health implications. Research by Calder et al. highlights that indoor PM2.5 levels during wildfires can reach up to 100% of outdoor concentrations in homes without air cleaners, showing the limitations of staying indoors with closed windows. However, air cleaners can reduce indoor PM2.5 by 63% to 88%, particularly in homes with low air exchange rates, and are recommended by researchers as a more effective mitigation strategy for people with respiratory issues. Complementing this, a study by Langford et al. underscores the broader impacts of wildfire smoke, which contains pollutants like nitrogen oxides (NOx) and volatile organic compounds (VOCs) that contribute to elevated ozone levels. In July 2021, pyrogenic ozone from wildfire emissions increased average 8-hour ozone levels in northern Colorado by 8 ppbv, with smoke plumes blanketing areas far from fire sources. Elevated ozone and PM2.5 levels pose severe risks to respiratory and cardiovascular health, with combined exposure being particularly harmful. These studies highlight the urgent need for policy changes, including promoting air cleaner use, reducing greenhouse gas and NOx emissions, and fostering regional collaboration to manage wildfire emissions. Without coordinated action, the increasing intensity and frequency of wildfires will continue to worsen air pollution and jeopardize public health across Colorado.

Motivation

Wildfires are increasingly common and severe in Colorado, posing serious risks to people's health, homes, and livelihoods. Smoke from these fires worsens air quality, leading to respiratory and cardiovascular problems, especially for children, the elderly, and vulnerable communities. Economic impacts are also significant, with rising insurance costs, declining property values, and disruptions to industries like tourism and construction. As the population grows in wildfire-prone areas like Centennial and the Denver Metro region, more people are exposed to these risks. Policymakers play a crucial role in addressing this crisis by implementing strategies for wildfire mitigation, improving air quality, and supporting economic resilience. This project aims to provide actionable insights to help decision-makers prioritize resources and policies that protect communities and reduce long-term harm.

Data

Combined wildland fire datasets for the United States

The Combined wildland fire datasets for the United States and certain territories, 1800s-Present (combined wildland fire polygons) dataset has details about all wildfires that have happened over the years all over the US. This dataset contains details about all wildfires that have occurred across the United States over the years. The USGS Wildland Fire Science

Program, which is responsible for this data, produces information to identify the causes of wildfires, understand their impacts and benefits, and help prevent and manage larger, catastrophic events4. This dataset is particularly significant as it provides a historical perspective on wildfire occurrences, allowing researchers and policymakers to analyze long-term trends and patterns in wildfire activity.

Air Quality Index (AQI) Data from U.S. Environmental Protection Agency's (EPA)

The dataset is sourced from the U.S. Environmental Protection Agency's (EPA) Air Quality System (AQS) API, which provides historical air quality measurements across the United States. While not offering real-time data, this database began standardized monitoring with quality assurance procedures in the 1980s, following the EPA's establishment in the early 1970s. The data collection typically initiated between 1983-1988 for most counties, though coverage varies geographically as some regions still lack monitoring stations. The API offers flexible data retrieval options through station IDs, county designations, or geographic bounding boxes, making it particularly valuable for spatial analysis. The measurements contribute to calculating the Air Quality Index (AQI), a key public health indicator frequently referenced in weather reports and environmental assessments, particularly during smog or smoke events.

Economic Indicators Data (FRED Economic Data)

The dataset covers a range of economic indicators for the Denver-Aurora-Lakewood, CO metropolitan area (CBSA/MSA) over various time periods. This comprehensive dataset, covering housing, labor, development, wages, prices, and population, will enable a robust analysis of how wildfire smoke events have influenced the economic health and resilience of the Denver-Aurora-Lakewood metropolitan area. By examining these indicators before, during, and after major wildfire occurrences, I can hopefully develop a more nuanced understanding of the far-reaching socioeconomic impacts beyond the immediate physical effects. All the datasets for various economic indicators used to analyze the impact on the Denver-Aurora-Lakewood region are detailed below, categorized by their respective characteristics.

1. **Housing Market Metrics:**
    - **Active Listings Count (2016–2024):** Tracks the number of active home listings, reflecting housing availability trends before, during, and after wildfire events.
    - **Median Listing Price per Square Foot (2016–2024):** Monitors changes in housing market valuations, shedding light on affordability and demand.
    - **Building Permits (Start Date Unknown):** Measures new private housing construction activity, indicative of developer confidence and market growth.
2. **Labor Market Data (Wages and Employment):**
    - **Unemployment Rate (1990–2024):** Provides long-term insights into labor market disruptions potentially caused by wildfire smoke.
    - **Average Hourly Earnings (2007–2024):** Tracks wage changes among private sector employees, reflecting wildfire smoke's economic impacts on workers.
    - **Per Capita Personal Income (1969–2022):** Measures overall economic well-being and resilience of residents in the metro area.
3. **Consumer and Market Metrics:**
    - **Market Hotness Rank (2017–2024):** A composite ranking for the Denver metro area consumer goods market, highlighting demand-supply dynamics.
    - **Consumer Price Index (1984–2023):** Indicates shifts in the cost of living, which may correlate with wildfire-related economic challenges.

Methodology

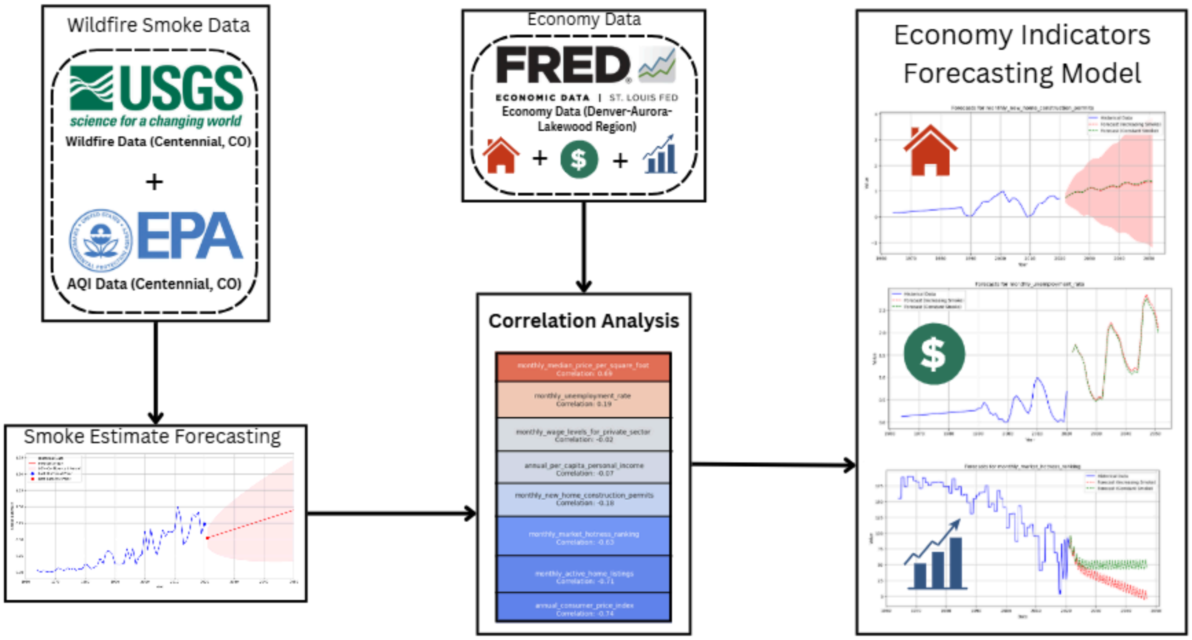


Figure (3): Data Flow and Methodology for the Analysis

Wildfire Data Acquisition

USGS Wildfire Dataset

The primary source of wildfire data used in this analysis is the **US Geological Survey (USGS) Wildfire Dataset**. This dataset provides a comprehensive historical record of wildfires across the United States, covering fire incidents from the 1800s to the present. It includes vital information such as the locations, sizes, and burn areas of wildfires, which is crucial for assessing the impact of these fires on surrounding areas.

The dataset is available in both ArcGIS and GeoJSON formats and contains fire polygons that describe the extent of each wildfire's perimeter. Given the large size of the dataset (nearly 2GB), direct storage in repositories can be challenging. However, the dataset can be accessed via links provided by the USGS website.

Wildfire Data for Centennial, CO

For the purposes of this analysis, wildfire data was filtered to focus specifically on wildfires near **Centennial, Colorado**. The goal was to retrieve the wildfire dataset from the USGS and compute the distance of each wildfire from Centennial. A distance of 650 miles from Centennial was chosen as the cutoff for relevant fires.

Air Quality Data

EPA Air Quality System (AQS) API

The **EPA Air Quality System (AQS) API** is a critical source for historical air quality data. The AQS provides standardized air quality measurements from monitoring stations across the United States, starting from the 1980s. These measurements are used to calculate the **Air Quality Index (AQI)**, a widely recognized indicator of air pollution levels.

The AQS API offers several methods for retrieving air quality data, including by station ID, county, or geographic bounding box. This flexibility is particularly useful for spatial analysis of air quality levels across different regions. For this report, air quality data for Centennial, CO, was extracted using the AQS API.

AQI Data for Centennial, CO

The above mentioned data was queried and air quality data was retrieved for Centennial from the EPA AQS API. The retrieved data was cleaned and processed to fill missing values, generating annual AQI estimates from 1964 to 2024.

Smoke Estimate Calculation

A **smoke estimate** was calculated to quantify the exposure to wildfire smoke in Centennial, CO, based on the proximity and intensity of nearby wildfires. This estimate serves as a proxy for the actual smoke levels experienced, as factors like wind direction, fire intensity, and fire duration are difficult to measure precisely.

The smoke estimate calculation considers several key factors:

- **Size Factor**
  Formula: `size_factor = np.log1p(acres) / np.log1p(1000)`
  The size of the fire perimeter, measured in acres, is logarithmically transformed to capture the non-linear relationship between fire size and smoke production.
- **Shape Length and Shape Area to Estimate Fire Duration**
  Formula: `duration_factor = min(30, sqrt(shape_area) / (shape_length / 1000))`
  Fire perimeter and area are used to estimate the duration of the fire's burn, with a cap at 30 days to reflect typical fire behavior.
- **Circleness Scale**
  Formula: `intensity_factor = 0.5 + Circleness_Scale / 2`
  The circularity of the fire's perimeter influences the intensity of the burn, with circular fires tending to produce more smoke due to uniform conditions.
- **Fire Classification Variable**
  Scale: Wildfire (5), Likely Wildfire (4), Prescribed Fire (3), Unknown (3), Other (1)
  The fire classification assigns a weight based on the origin and management status of the fire, with uncontrolled wildfires receiving higher weights.
- **Distance Decay Factor**
  Formula: `distance_factor = 1 / (1 + (distance / 50) ** 2)`
  The distance from the fire to the point of interest is inversely related to the smoke impact, with the effect reducing as distance increases.
- **Final Calculation**
  Formula: `smoke_impact = size_factor * distance_factor * intensity_factor * duration_factor * fire_intensity_factor`
  The final smoke impact score is calculated by multiplying the factors, resulting in a value scaled from 0 to 100 for intuitive interpretation.

These factors were combined into a comprehensive smoke estimate formula.

Economic Indicator Grouping and Feature Engineering

The economic indicators data mentioned in the previous section were categorized into three main groups to facilitate a structured analysis.

Data Normalization and Population Adjustment

In the methodology of this study, two important data preprocessing steps were implemented to ensure fair comparisons across variables and to account for population changes over time.

Min-Max Scaling

All variables in the study were normalized to a scale of 0-1 using min-max scaling. This technique is applied to bring all variables to a common scale, which is particularly useful when dealing with variables that have different units or ranges.

The min-max scaling formula is:

$$X_{scaled} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

This transformation results in all variables having values between 0 and 1, where 0 represents the minimum value in the original dataset and 1 represents the maximum value.

Population Adjustment for Housing Market Variables

Variables in the housing market category were adjusted by dividing by annual population data. This adjustment accounts for population changes over time, which is crucial for accurately interpreting housing market trends.

This adjustment helps to normalize housing market indicators relative to the population size, allowing for more meaningful comparisons across different time periods when population growth might otherwise skew the data.

By implementing these data preprocessing steps, the study ensures that:

1. All variables are on a comparable scale, facilitating easier interpretation and analysis.
2. Housing market indicators are adjusted for population changes, providing a more accurate representation of market trends over time.

These techniques contribute to the robustness of the analysis and help in drawing more reliable conclusions about the potential impacts of wildfire smoke on various economic indicators.

Correlation Analysis of Smoke Estimate with Economic Indicators

A Pearson correlation analysis was performed to identify the most correlated variables within each economic group. This step helps in understanding the strength and direction of relationships between smoke estimates and various economic indicators.

Multilevel Analysis Approach

The core of the methodology involves a three-tiered analysis approach:

Yearly Level Analysis

- Compare yearly averages of economic indicators under both constant and increasing smoke scenarios.
- Identify broad trends and significant differences between scenarios.

Monthly Data Analysis

- For indicators showing notable differences at the yearly level, conduct a more granular analysis using monthly data.
- Examine subtle patterns and seasonal variations that may not be apparent in yearly data.

Wildfire vs. Non-Wildfire Months Comparison

- Specifically analyze data during wildfire months (typically July-October) versus non-wildfire months.
- Isolate the direct effects of increased smoke exposure on economic indicators.

For each of the three economic sectors, the multi-level analysis approach is applied:

1. Housing Market Analysis
    - Examine monthly active home listings, median price per square foot, and new home construction permits.
    - Analyze how these indicators fluctuate with changing smoke estimates.
2. Wages and Employment Analysis
    - Investigate per capita personal income, unemployment rates, and private sector wage levels.
    - Assess the potential impact of smoke on employment trends and wage growth.
3. Consumer Goods Market Analysis
    - Study consumer price index and market hotness rankings.
    - Evaluate how consumer behavior and market dynamics may shift with varying smoke levels.

SARIMAX Model Overview

Model Structure

SARIMAX is an extension of the ARIMA (AutoRegressive Integrated Moving Average) model, incorporating both seasonal components and exogenous variables. In this analysis the SARIMAX model was used to forecast all the economic indicators by using the forecasted smoke estimate as the exogenous variable. The model is represented by the following formula:

- **SARIMA(p,d,q)(P,D,Q)m**

Where:

- **(p,d,q)** are the non-seasonal parameters:
    - **p**: Number of autoregressive terms
    - **d**: Degree of differencing required to make the series stationary
    - **q**: Number of moving average terms
- **(P,D,Q)** are the seasonal parameters:
    - **P**: Number of seasonal autoregressive terms
    - **D**: Degree of seasonal differencing
    - **Q**: Number of seasonal moving average terms
- **m**: Number of periods in each season (e.g., 12 for monthly data)

Model Components

SARIMAX combines the following components:

- **Autoregression (AR)**: Uses past values of the series to predict future values.
- **Integration (I)**: Differencing of the data to make the series stationary.
- **Moving Average (MA)**: Incorporates past forecast errors in predicting future values.
- **Seasonal Components (S)**: Accounts for repeating seasonal patterns, which is crucial for economic data that exhibits cyclical fluctuations.
- **Exogenous Variables (X)**: Includes external factors that influence the target variable, such as wildfire smoke estimates in this case.

Economic indicators often exhibit seasonal fluctuations, such as retail sales increasing during holiday seasons or construction activities peaking in summer months. SARIMAX is well-equipped to capture these seasonal patterns, making it an ideal model for forecasting economic data that exhibits periodic variations.

In addition to seasonality, economic data may display long-term trends and short-term cyclical behavior. The SARIMAX model is capable of accounting for both types of patterns, providing a comprehensive understanding of economic dynamics.

One of the key strengths of SARIMAX is its ability to include **exogenous variables**. In this project, the wildfire smoke estimate was included as an exogenous variable, enabling the analysis of its impact on various economic indicators. This inclusion allows for a more nuanced understanding of how external environmental factors influence economic outcomes.

Economic time series data often exhibits non-stationarity, meaning that its statistical properties change over time. SARIMAX can handle non-stationary data through differencing, which makes it suitable for analyzing economic indicators that may not have constant mean or variance.

The SARIMAX model is highly flexible, with adjustable parameters that can be tuned to fit different types of time series data. This versatility makes it an ideal choice for analyzing a variety of economic indicators, as it can be adapted to capture the unique patterns within each dataset.

Impact of Smoke Scenarios on Economic Indicator Variables

For each economic indicator variable, the analysis calculates the **average predicted impact** and the **maximum predicted impact**. The **average predicted impact** is determined by taking the difference between the forecast under the increasing smoke scenario and the forecast under the constant smoke scenario, dividing by the constant scenario's forecast, and multiplying by 100 to express the result as a percentage. This provides an average estimate of how much the target variable changes when smoke levels are projected to rise. Additionally, the **maximum predicted impact** identifies the largest percentage difference between the two scenarios, offering insight into the extreme effects of increasing smoke levels.

Impact Analysis Formulas

Average Predicted Impact Formula:

$$\text{Average Impact} = \frac{\text{forecast\_increasing} - \text{forecast\_constant}}{\text{forecast\_constant}} \times 100$$

The **average predicted impact** computes the percentage difference between the two forecasts and averages the result across all future periods.

Maximum Predicted Impact Formula:

$$\text{Maximum Impact} = \max\left(\frac{\text{forecast\_increasing} - \text{forecast\_constant}}{\text{forecast\_constant}} \times 100\right)$$

The **maximum predicted impact** finds the largest percentage difference between the forecasts for the increasing and constant smoke scenarios.

Methodology: Human-Centered and Ethical Considerations

The study aimed to address the real-world effects of wildfire smoke, such as health risks, economic challenges, and social inequalities. For instance, the **Forecasted Smoke Estimate** was designed to help policymakers prioritize areas like Centennial, CO, where vulnerable populations might experience the most significant impacts. By aligning research goals with actionable insights, the study sought to ensure its findings would contribute positively to affected communities.

The analysis accounted for disparities in wildfire smoke exposure, focusing on regions with greater vulnerabilities. The **Distance Decay Factor** emphasized the proximity of wildfires to population centers, ensuring that areas experiencing the highest exposure received the most attention in the analysis. This approach highlighted the importance of addressing inequities, such as those faced by economically disadvantaged populations or high-risk zones.

Transparency was prioritized by documenting all assumptions, limitations, and uncertainties. For example, the study used a simplified formula for **Fire Duration** (`min(30, sqrt(shape_area) / (shape_length / 1000))`) to estimate burn time while acknowledging the absence of direct atmospheric data. This ensured that stakeholders could evaluate the model's constraints and interpret the results accurately.

Efforts were made to reduce biases by incorporating diverse datasets, such as the **EPA Air Quality System (AQS) API** for air quality trends and the **USGS Wildfire Dataset API** for historical wildfire data. Sensitivity checks were conducted to handle gaps in data, like missing GIS acres for specific years, ensuring the analysis was fair and balanced.

The findings were framed to support solutions that promote long-term sustainability and resilience. For instance, forecasts for **housing permits** and **market hotness rankings** were designed to inform policy changes, such as zoning adjustments or investments in wildfire mitigation. By linking environmental data to economic outcomes, the study emphasized the broader societal and environmental implications of its findings.

Although the study relied on publicly available data, it ensured that sensitive information was protected. For example, when analyzing smoke impacts on economic indicators like **Annual Per Capita Income**, data was aggregated and anonymized to safeguard community privacy while still providing meaningful insights.

The study adhered to established ethical guidelines and underwent regular reviews to ensure fairness and accountability. For instance, the **ARIMAX forecasting model** explicitly acknowledged its limitations, such as the assumption of constant relationships between variables over time..

Findings and Implications

Temporal Trends and Spatial Distribution of Wildfire Impacts

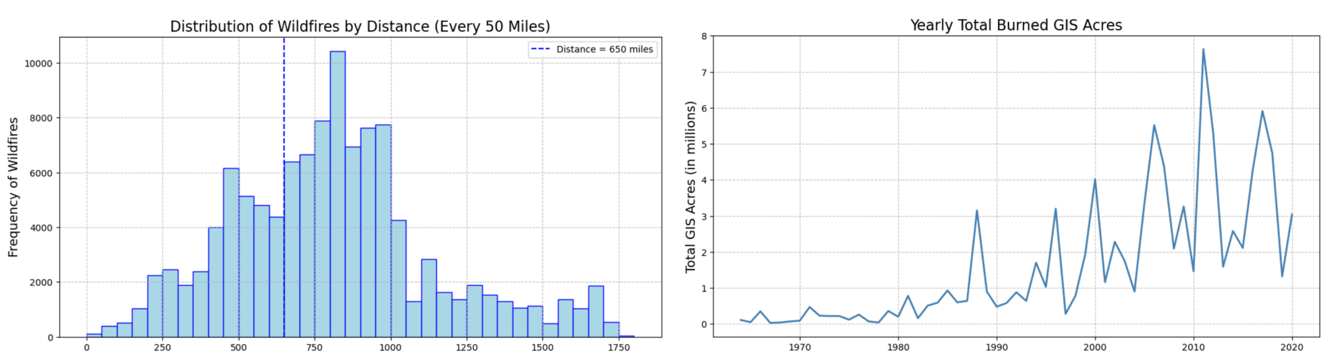


Fig 4(a): Distribution of Wildfires by Distance, Fig 4(b) Yearly Total Burned GIS Acres

This histogram on the left illustrates the distribution of wildfires based on their distance from the latitude and longitude reference point, with each bar representing a 50-mile range. The distribution is unimodal and approximately symmetric, with a clear peak around 750 miles. This suggests that most wildfires tend to occur within a specific distance range, notably between 500 and 1000 miles from the reference point. While the majority of data points fall within the central range, a few wildfires occur at farther distances, extending up to around 1750 miles, though these instances are less common.

This line plot on the right shows the yearly total burned GIS acres (in millions) from the early 1960s to the 2020s. The trend indicates a relatively low and stable number of burned acres from the 1960s to the 1990s, with only minor fluctuations. However, starting around the year 2000, there is a noticeable increase in burned acres, with significant spikes in certain years. The most extreme peak occurs around 2010, reaching nearly 80 million acres. This increase in burned acreage over recent decades could reflect factors such as rising temperatures, drier conditions, or other environmental changes, highlighting the intensifying impact of wildfires in recent years.

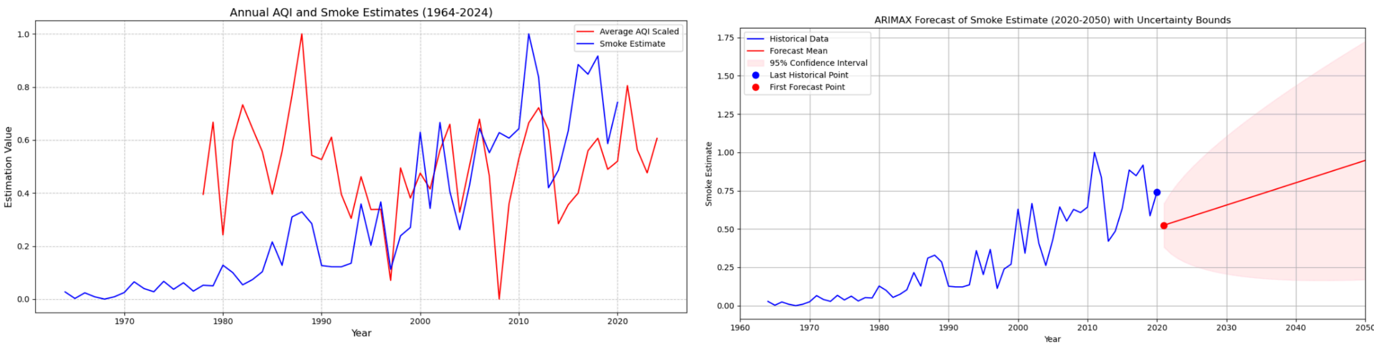


Fig 5(a): Annual AQI and Smoke Estimate, Fig 5(b) ARIMAX Forecast of Smoke Estimate

This line chart on the left shows the trends of Average AQI (Air Quality Index) and Smoke Estimates from 1964 to 2024, both normalized on a scale from 0 to 1. The Average AQI Scaled shows an overall increase with peaks in the mid-1980s, early 2000s, and early 2010s, alongside occasional declines. The Smoke Estimate steadily rises, especially after the 1980s, with notable peaks in the early 2000s and post-2010, reflecting wildfire activity. The chart suggests a correlation between higher smoke events and AQI values, though inconsistently, and indicates a general decline in air quality and an increase in smoke events over time.

The forecast on the right of the smoke estimate suggests a continuation of this upward trend into the future, indicating an expectation of increased smoke impact over time. Given that the historical data shows a steady rise in recent years, this upward forecast seems reasonable. The confidence interval starts relatively narrow in 2021 but fans out considerably as it moves further into the future, covering a much broader range by 2050.

Impact of Wildfire Smoke on Housing Market Trends and Construction Activity

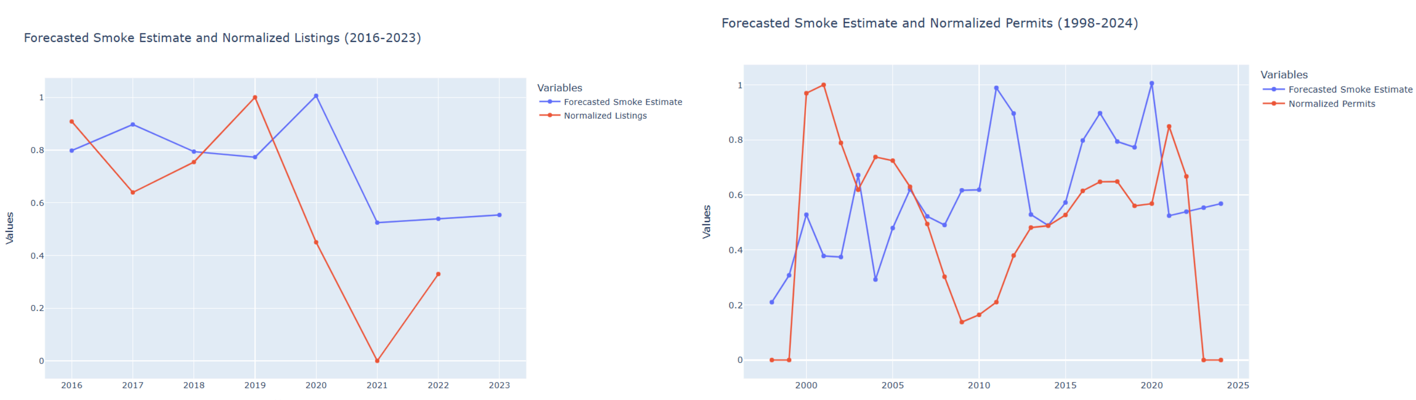


Fig 6(a): Forecasted Smoke Estimate and Normalized Listings, Fig 6(b) Forecasted Smoke Estimate and Normalized Permits

The relationship between forecasted smoke estimates and normalized housing listings in the Denver-Aurora-Lakewood region (2016-2023) shows notable patterns. The smoke estimate fluctuated with a decline after peaking in 2019, reaching its lowest in 2021 before stabilizing. This decline coincided with intense wildfire activity in 2020-2021 and a housing supply deficit. Despite ongoing air quality challenges, housing listings recovered sharply between 2021 and 2022, driven by factors like insurance industry adjustments and market changes. By 2023, the market showed signs of normalization, with higher listings and a population growth of 1.2% from 2020-2023. The data reflects a complex interaction between environmental risks and housing market behavior, suggesting adaptation to increased wildfire risks.

The Denver-Aurora-Lakewood region has seen significant fluctuations in building permits for new private housing structures, with a 38% increase in permits issued in 2022 compared to the previous year. From 2016 to 2019, permit activity was relatively stable, but the pandemic years (2020-2021) saw a sharp decline due to supply chain disruptions and labor shortages. In the recovery phase (2021-2023), permit activity gradually increased to address the region's housing shortage, with projections indicating a demand for 36,100 new units by 2026. Key contributing factors include environmental concerns, such as wildfire risks influencing development patterns, and market dynamics like rising home prices (over 40% in the last five years), population growth, and higher interest rates, which are shaping the region’s housing market.

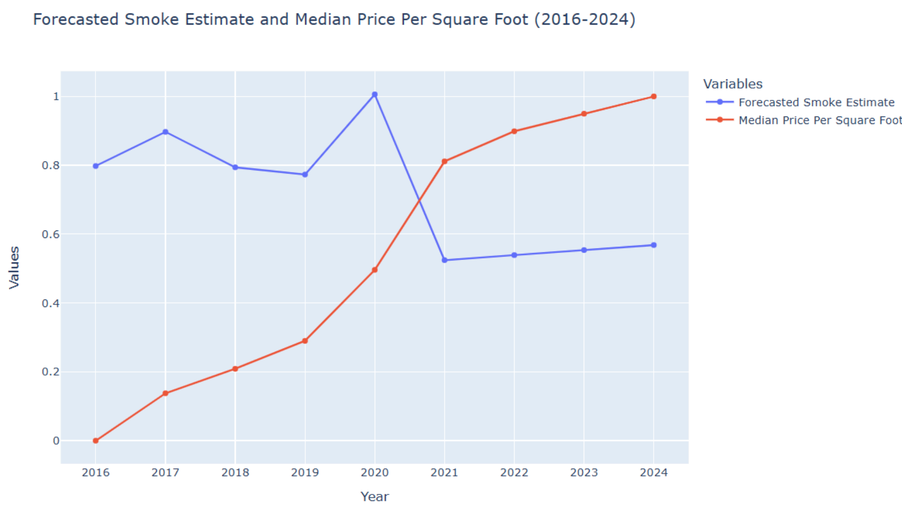


Fig 7: Forecasted Smoke Estimate and Median Price Per Square Foot

The median price per square foot in the Denver-Aurora-Lakewood area has steadily increased since 2016, accelerating between 2020-2021 and reaching 1.0 by 2024, reflecting rising housing costs. A comparison of forecasted smoke estimates and active home listings from 2016-2024 reveals distinct patterns. Smoke estimates peaked in 2019, then declined and stabilized by 2021, while active home listings decreased until 2021 before gradually recovering through 2024, indicating loosening market constraints. The drop in smoke estimates in 2020 coincided with a housing inventory low, suggesting broader market influences. Despite ongoing wildfire risks and rising home prices, inventory has increased, but affordability remains a challenge. The region faces a projected need for 200,000 new housing units by 2050, with a significant housing supply deficit, yet continues to adapt to environmental and economic pressures.

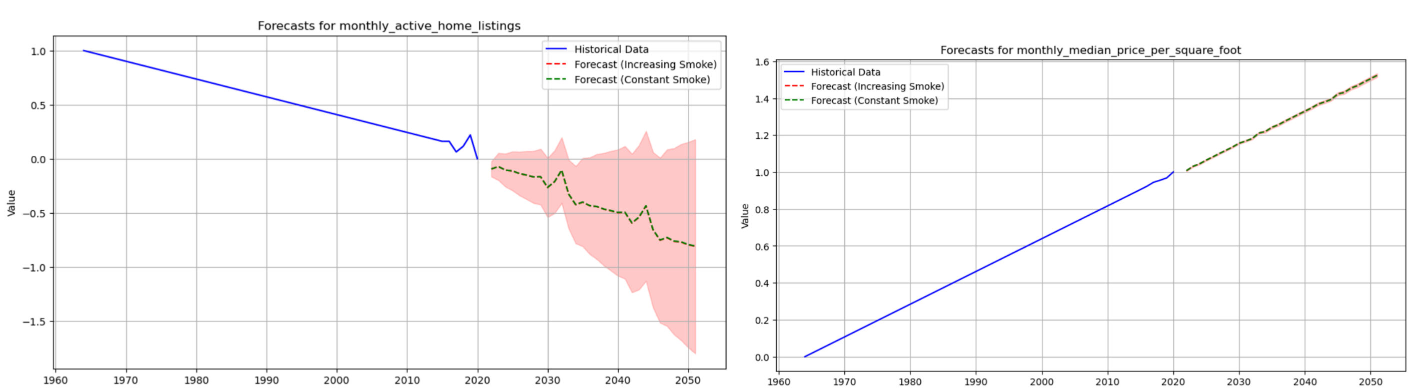


Fig 8(a): Forecasted Monthly Active Home Listings, Fig 8(b): Forecasted Monthly Median Price per Square Foot

The trend of active home listings over time shows a steady decline from 1960 to the present, with historical data depicted in blue. Two forecast scenarios are presented: one where smoke levels increase (red dashed line) and one where smoke levels remain constant (green dashed line). The forecast under the increasing smoke scenario shows an accelerated decline in home listings over the next few decades, whereas the constant smoke scenario predicts a more stable, but still declining trend. The difference suggests that increasing smoke levels could exacerbate the reduction in active home listings.

The historical data for median price per square foot shows a consistent upward trend from 1960, indicating rising housing costs. Both forecast scenarios predict continued growth in price per square foot, with the increasing smoke scenario showing a stronger rate of growth compared to the constant smoke scenario. However, the difference is relatively small and not significant enough to warrant further detailed analysis. For the purposes of this report, the impact on price per square foot is noted but excluded from the main analysis.

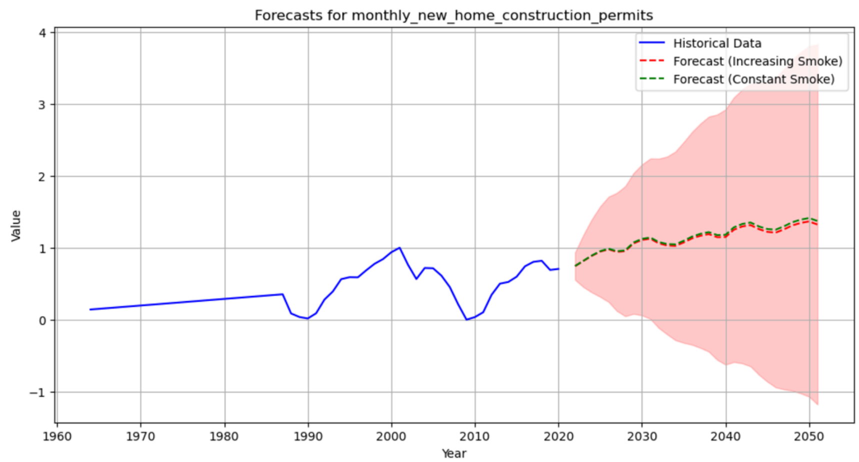


Fig 9: Forecasted Monthly New Home Construction Permits

The graph for new home construction permits from 1960 to 2050 shows fluctuations, with notable dips around 1990 and 2010. Both forecasts predict an upward trend in permits, suggesting future growth in construction. However, the increasing smoke scenario predicts slightly more volatility and lower permit numbers, indicating that higher smoke levels could modestly hinder construction activity. This distinction warrants further analysis on the impact of wildfire-related smoke on new home construction permits.

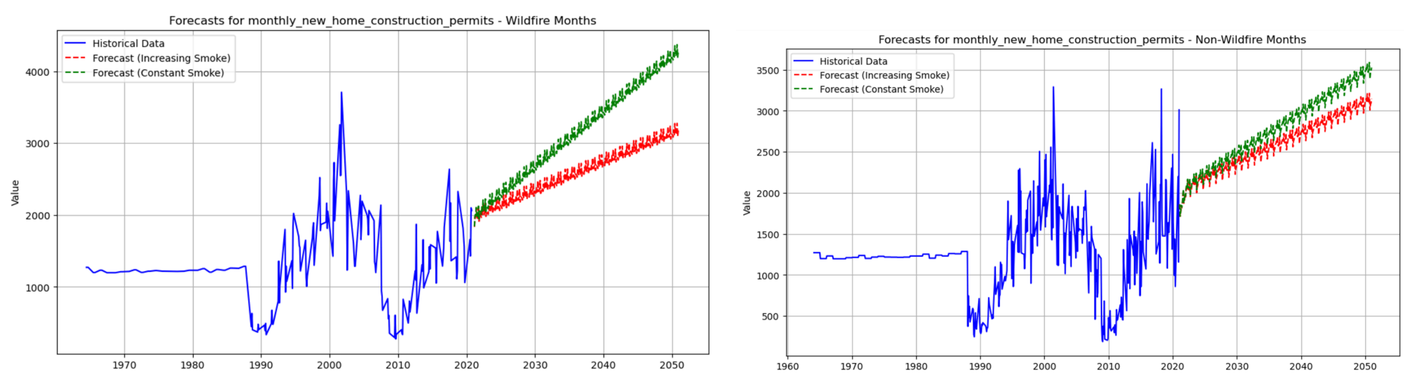
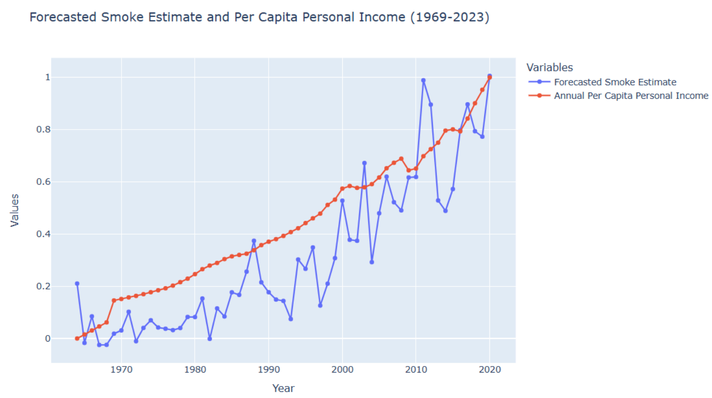


Fig 10(a): Forecasted Monthly Active Home Listings, Fig 10(b): Forecasted Monthly Median Price per Square Foot

The graphs compare forecasted monthly new home construction permits in the Denver-Aurora-Lakewood region during wildfire and non-wildfire months, under two scenarios: increasing and constant smoke levels. Historical data shows significant fluctuations in construction activity, with peaks and valleys influenced by economic conditions, population growth, and wildfire-related challenges. During wildfire months, the increasing smoke scenario predicts slower growth, due to factors like stricter regulations, reduced area desirability, and higher insurance costs, all of which hinder construction. Conversely, non-wildfire months show more stable construction activity, with higher permit levels and a narrower difference between the increasing and constant smoke scenarios.

Economic and Labor Market Dynamics in the Context of Wildfire Smoke



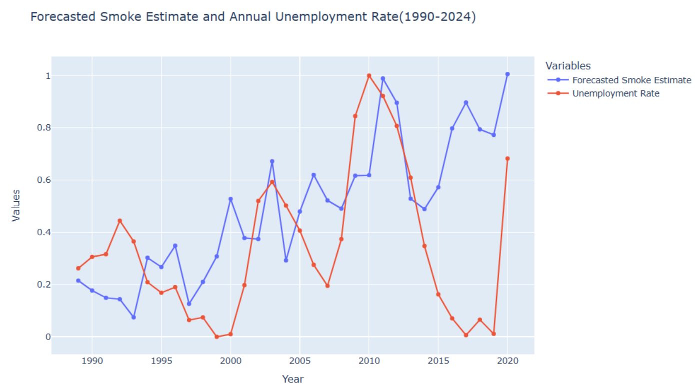


Fig 11(a): Forecasted Smoke Estimate and Per Capita Personal Income, Fig 11(b): Forecasted Smoke Estimate and Annual Unemployment Rate

The left graph compares the Forecasted Smoke Estimate and Annual Per Capita Personal Income from 1969 to 2023, shows an overall upward trend in both variables, with some fluctuations. The increase in the smoke estimate is linked to rising wildfire frequency and severity in the Western United States, driven by climate change. The growth in personal income is attributed to factors such as population growth, economic development, and increased productivity in the Denver metro area, along with broader economic trends like inflation.

The right graph depicts the Forecasted Smoke Estimate and Annual Unemployment Rate from 1990 to 2024, shows a more complex relationship. While the smoke estimate continues to rise, the unemployment rate exhibits greater volatility. The initial decline in unemployment may reflect the negative economic impacts of wildfires and smoke, such as reduced business investment. However, the later stabilization suggests that the region has adapted, potentially through mitigation efforts or changes in behavior, with broader economic cycles also influencing unemployment trends.

Fig 12: Forecasted Smoke Estimate and Annual Wage Levels for Private Sector

This graph shows a synchronized upward trend in both the Forecasted Smoke Estimate and Annual Private Sector Wage Levels from 2007 to 2024. The rise in wages is likely influenced by factors such as economic growth, labor market tightness, and productivity improvements in the region. Overall, these trends illustrate the complex interplay of environmental, economic, and demographic factors in the Denver-Aurora-Lakewood region, providing valuable insights for addressing wildfire impacts and promoting sustainable development.

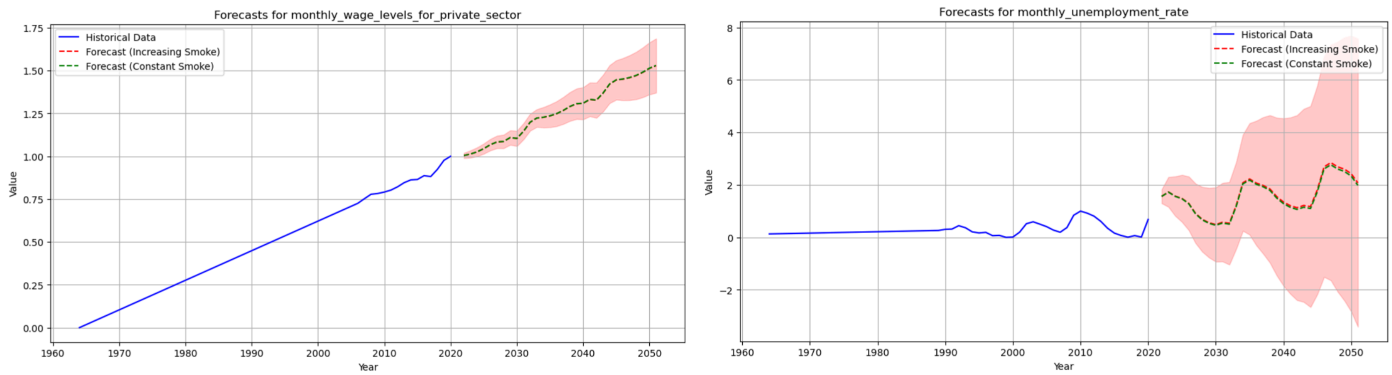


Fig 13(a) Forecast for Monthly Wage Levels, 13(b) Forecasts for Monthly Unemployment Rate

The left graph, the forecast suggests that private sector wages are expected to rise over time, but the impact of increasing smoke leads to a divergence in projected wage growth. Under constant smoke levels, wage growth remains steady and predictable, following a relatively smooth upward trajectory. However, the increasing smoke scenario introduces greater uncertainty, represented by the widening confidence intervals (shaded red area) and slightly higher wage projections on average. This could indicate that smoke-related factors (such as health impacts or productivity declines) might initially push wages higher due to inflationary pressures or compensatory mechanisms, but the broader uncertainty suggests potential destabilizing effects on labor markets.

The right graph, the unemployment forecasts paint a different picture. While historical data show relatively stable unemployment rates, projections under the increasing smoke scenario reveal significant volatility, with a sharp increase in uncertainty over time. This suggests that increasing smoke levels might have a destabilizing effect on employment, possibly due to disruptions in industries, regional impacts, or adverse health effects reducing workforce participation. In contrast, under constant smoke levels, unemployment is projected to remain stable, with much tighter confidence intervals. This stability underscores the critical importance of mitigating environmental degradation to maintain economic resilience.

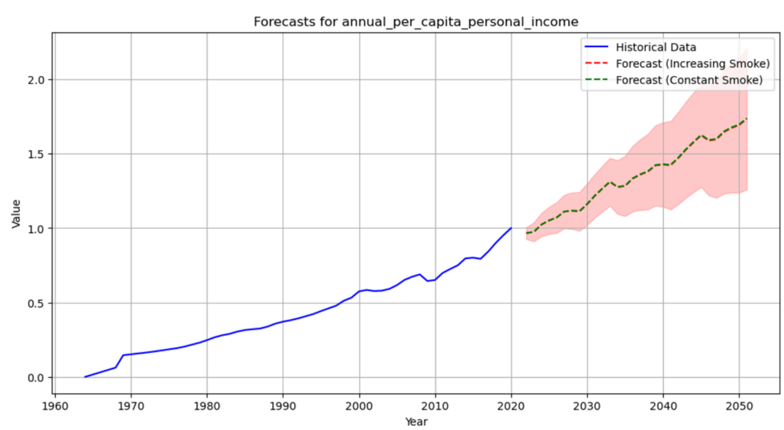


Fig 14: Forecasts for Per Capita Income

This graph illustrates forecasts for annual per capita personal income. From 1960 to 2020, the historical trend shows a steady rise in income, reflecting consistent economic growth. Looking ahead from 2020 to 2050, the constant smoke scenario predicts a smooth upward trajectory, continuing the historical growth pattern. In contrast, the increasing smoke scenario suggests slightly higher income growth initially but with significantly greater uncertainty, as indicated by the widening shaded region. This uncertainty highlights the potential economic instability caused by environmental factors such as health impacts and productivity disruptions.

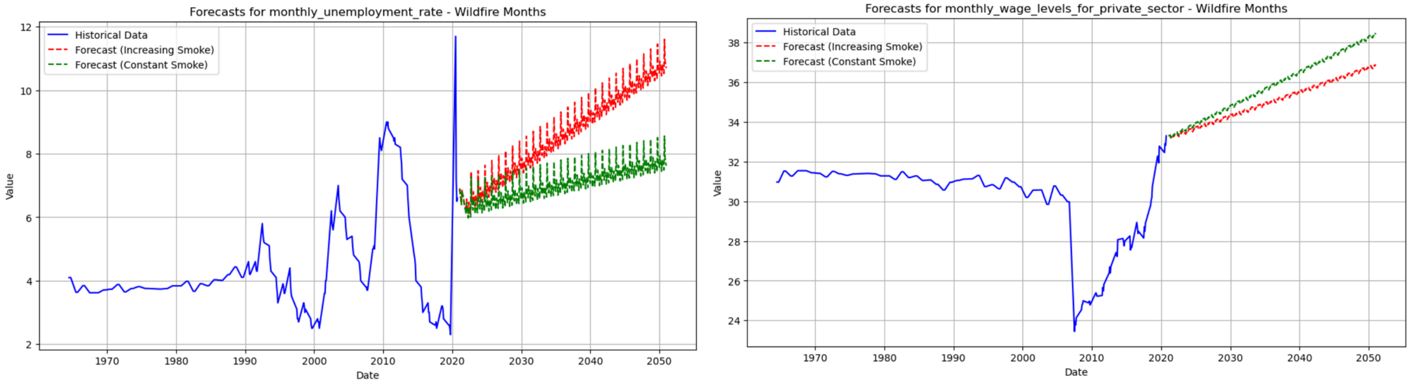


Fig 15(a) Forecast for Monthly Unemployment Rate, 15(b) Forecasts for Monthly Wage Levels for Private Sector

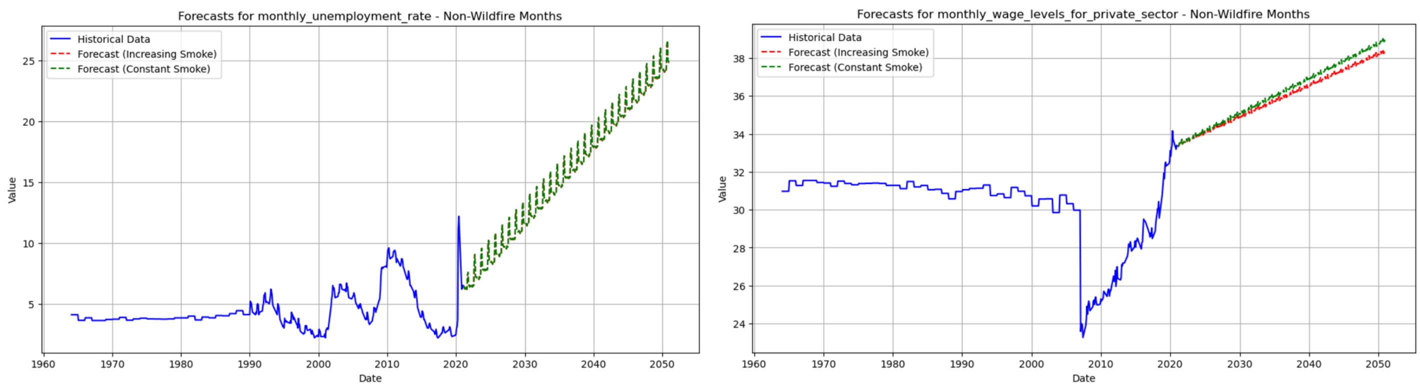


Fig 15(c) Forecast for Monthly Unemployment Rate, 15(d) Forecasts for Monthly Wage Levels for Private Sector

The graphs compare forecasted monthly new home construction permits in the Denver-Aurora-Lakewood region during wildfire and non-wildfire months, under two scenarios: increasing smoke levels and constant smoke levels. In the first graph, which focuses on wildfire months, historical data shows significant fluctuations in construction activity, with a decline in the 1990s likely due to economic recessions or increased wildfire activity. The forecast with constant smoke levels suggests better growth compared to increasing smoke levels, which are projected to hinder construction due to stricter regulations, higher insurance costs, and reduced desirability of affected areas. Wildfire months are challenging for construction due to damage, resource shortages, and heightened costs.

In the graphs, examining non-wildfire months, construction activity is generally more stable and higher than during wildfire months. The difference between the two scenarios is narrower here, indicating that while increasing smoke levels still impact construction, the effect is less severe in non-wildfire months. Health risks and environmental degradation during wildfire months reduce demand for housing, while cleaner air during non-wildfire months fosters steady growth. These trends highlight how environmental factors, economic constraints, and population dynamics shape the construction industry. The gap between the two smoke scenarios underscores the increasing challenges that worsening smoke levels may pose to future construction activity.

Impact of Wildfire Smoke on Consumer Prices, Market Activity, and Seasonal Trends

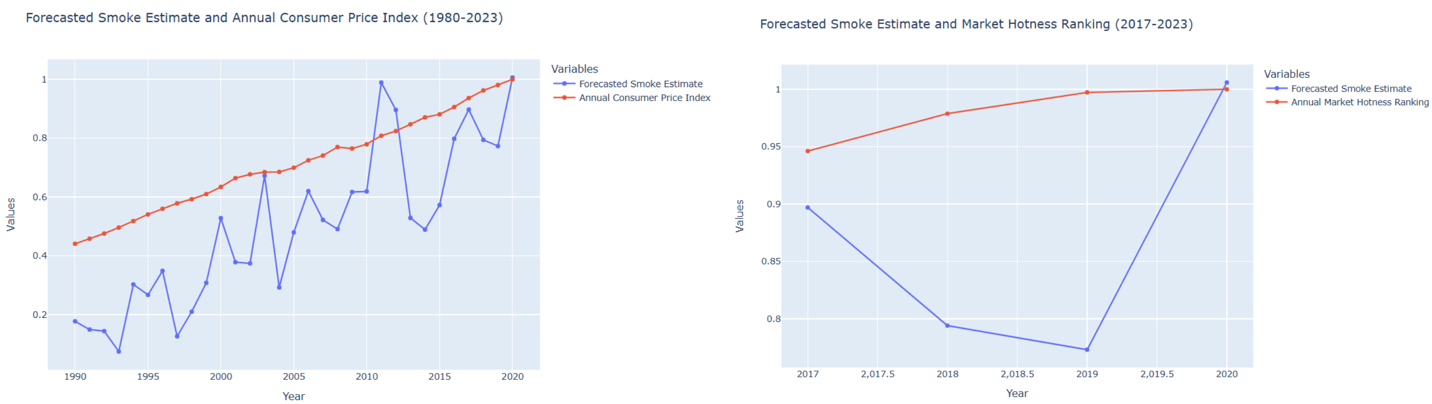


Fig 16(a) Forecasted Smoke Estimate and CPI, 16(b) Forecasted Smoke Estimate and Market Hotness Rank

The left graph shows two trends from 1990 to 2023: the Forecasted Smoke Estimate and the Annual Consumer Price Index (CPI). The CPI steadily rises, indicating long-term inflation, while the Smoke Estimate fluctuates significantly, reflecting the unpredictable nature of wildfires and environmental conditions. Both variables show upward trends, with rising smoke levels linked to climate change and wildfires, and the CPI increase driven by factors like inflation, population growth, and economic development.

The right graph compares the Forecasted Smoke Estimate and Annual Market Hotness Ranking from 2017 to 2020, both normalized between 0 and 1. The Market Hotness Ranking shows a steady increase, indicating growing market activity, while the Smoke Estimate declines sharply from 2017 to 2019 and rises sharply in 2020. This volatility suggests external factors like environmental changes and wildfires influencing smoke levels. The divergence between the two trends may imply different underlying dynamics. The rise in smoke estimates in 2020 could reflect increased wildfire activity, while the housing market's adaptation may be due to changing preferences and mitigation strategies.

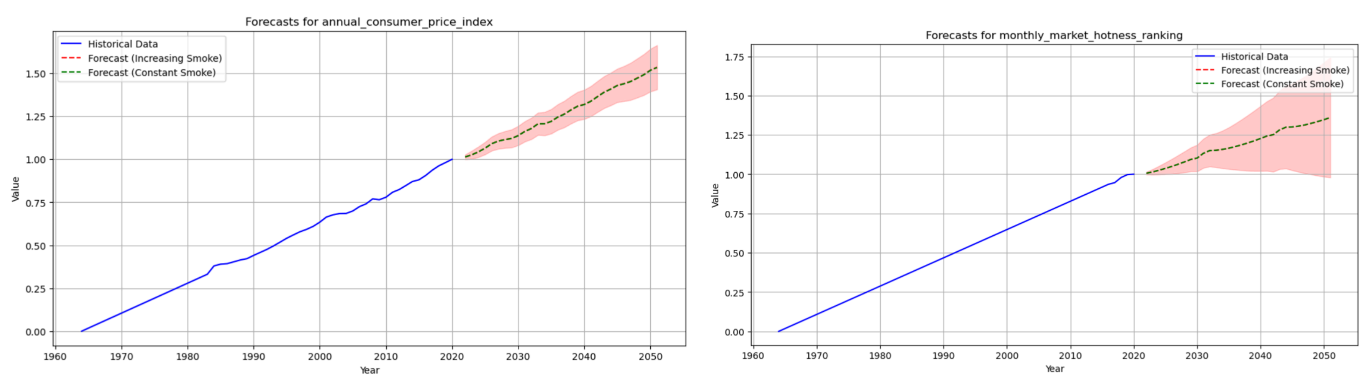


Fig 17(a) Forecasts for CPI, 16(a) Forecasts for Market Hotness Rank

The two graphs show the historical and forecasted trends for the Annual Consumer Price Index (CPI) and Monthly Market Hotness Ranking, comparing scenarios of increasing and constant smoke exposure. The CPI has risen steadily from 1960 to 2020, with forecasts under increasing smoke exposure predicting a sharper rise after 2024, along with higher uncertainty. Constant smoke exposure results in a more moderate CPI increase. For the Market Hotness Ranking, historical data shows consistent growth, but increasing smoke exposure leads to a steeper rise with greater variability, while constant exposure predicts a slower, more stable increase. Both scenarios highlight the potential economic risks of rising smoke levels.

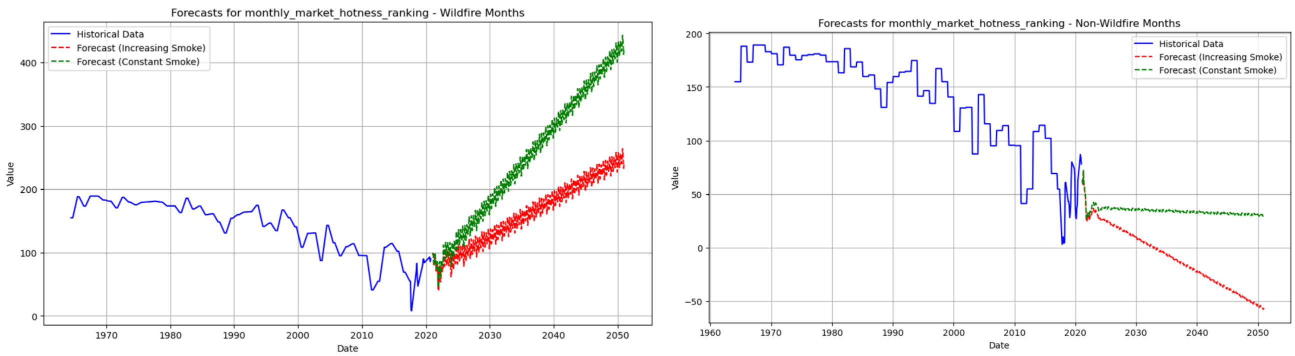


Fig 18(a) Forecasts for Market Hotness Rank - Wildfire Months, 18(a) Forecasts for Market Hotness Rank - Non-Wildfire Months

The graphs display market hotness rankings across wildfire and non-wildfire months from 1960 to 2050, with historical data showing stability during wildfire months and a gradual decline during non-wildfire months. Future forecasts under two scenarios—increasing smoke impact and constant smoke impact—reveal stark contrasts. Increasing smoke exposure projects a sharp rise in wildfire months, reaching 250 by 2050, while non-wildfire months decline into negative values. Constant smoke exposure predicts an even steeper rise in wildfire months (surpassing 400 by 2050) and stable, positive values for non-wildfire months. These projections highlight a shift in market behavior, with environmental conditions becoming a key factor in market performance. Stakeholders, including investors and developers, may need to adjust strategies to account for the growing seasonality and volatility driven by smoke impacts, suggesting a need for year-round resilience rather than seasonal adaptations.

Discussions

Housing Market Trends and Construction Activity

Importance of Findings

The analysis reveals significant disruptions in the housing market and construction activity due to wildfire smoke. Housing inventory showed sharp declines during periods of intense wildfire activity, reflecting increased risks and decreased desirability in affected regions. Median home prices have continued to rise, compounding affordability challenges for residents. Construction permits, although recovering in recent years, exhibit volatility linked to smoke exposure and other environmental factors. These findings underscore the growing tension between population growth and the capacity to provide safe, affordable housing in regions like the Denver-Aurora-Lakewood area.

Recommendations for Action

City councils and local governments should prioritize zoning reforms to incentivize development in lower-risk areas while investing in fire-resistant infrastructure and materials. Building codes should be updated to include wildfire mitigation measures, such as creating defensible spaces and requiring fire-resistant building designs. Residents can reduce risks by retrofitting homes and maintaining vegetation buffers. These changes should be integrated into long-term urban planning policies within the next 5–10 years to address both immediate risks and future population growth

Labor Market and Economic Resilience

Wildfire smoke has a dual impact on the labor market: reducing workforce participation due to health-related issues while driving temporary employment in disaster management and reconstruction. These trends reveal a concerning pattern of short-term job boosts followed by long-term instability. Wage levels may rise in the private sector as businesses respond to labor shortages, but this does not offset the broader economic disruptions caused by declining productivity and increased healthcare costs.

Recommendations for Action

Local governments must collaborate with state and federal agencies to support workforce resilience. This includes creating economic safety nets, offering job training programs for affected industries, and ensuring equitable access to healthcare resources. The city manager should work with local businesses to promote remote work policies during wildfire seasons, reducing smoke exposure and maintaining productivity. Immediate action is required to implement these measures, with a target of full preparedness within 3–5 years.

Consumer Prices and Market Activity

The analysis shows that wildfire smoke contributes to inflationary pressures, particularly in consumer goods and housing-related costs. The Consumer Price Index (CPI) demonstrates consistent growth, while market hotness rankings reflect increased demand for properties in less vulnerable areas. This indicates that wildfire smoke not only impacts air quality but also exacerbates economic inequality, as wealthier residents are better positioned to relocate or invest in mitigation strategies. These trends highlight the interconnected nature of environmental hazards and economic challenges, making this a critical issue for policymakers.

Recommendations for Action

City councils and mayors should work to stabilize the local economy by implementing smoke-resilient policies, such as incentivizing businesses to stockpile essential goods and invest in air filtration systems. Subsidies for low-income households to access air purifiers and healthcare support during wildfire seasons are also essential. On a broader scale, local governments must advocate for state and federal funding to address inflationary impacts caused by wildfires. Concrete plans must be enacted within 2–3 years to prevent further economic polarization.

Limitations

The smoke impact estimation model incorporates valuable insights but is constrained by several limitations and uncertainties:

1. **Data Gaps and Quality:**
   - Missing AQI data and gaps in gaseous and particulate datasets (e.g., 1964–1977, 2008, 1995–1998) limit accuracy.
   - Historical wildfire data may lack consistent collection methods.
2. **Temporal Misalignment:**
   - Datasets vary in time ranges and frequencies (e.g., monthly vs. annual), complicating direct correlations. Advanced normalization methods are required to align and analyze the data effectively.
3. **Geographic Scope Issues:**
   - Centennial's incorporation in 2001 limits city-specific data, embedding it within Denver-Aurora-Lakewood MSA data. This aggregation may obscure localized effects. Sparse and inconsistent post-2001 data adds further challenges.
4. **Model Assumptions:**
   - The ARIMAX model assumes linear and constant relationships, which may oversimplify dynamic and complex interactions, especially in the context of climate change and fire management evolution.
5. **Data Aggregation:**
   - Aggregating AQI, smoke, and economic indicators can obscure trends and seasonal variations critical for analysis.
6. **Confounding Variables:**

    - Economic trends are influenced by external factors such as the 2008 financial crisis, COVID-19, inflation, and regional policies, complicating smoke-specific impact isolation.
7. **Causality Challenges:**
    - Disentangling smoke effects from other environmental factors is difficult. Lagging economic changes and cumulative smoke events further complicate causal relationship establishment.

Conclusions

This project set out to explore how wildfires and their smoke affect the economy and well-being of communities, particularly in the Denver-Aurora-Lakewood region. The main goals were to understand the impact of wildfire smoke on housing, labor markets, consumer prices, and overall health.

The findings show that wildfires disrupt the housing market, making homes more expensive and limiting new construction. Labor markets face instability as smoke impacts worker health and productivity, while consumer goods become more expensive due to inflation driven by environmental risks. Health effects are especially severe for vulnerable groups, highlighting the need for public health interventions.

This study demonstrates how human-centered data science can provide insights that directly help people. By focusing on fairness, equity, and transparency, this analysis highlights the real-world effects of wildfires on communities and offers solutions to reduce these impacts. The findings give city leaders, residents, and policymakers a clear path to making informed decisions that prioritize the well-being of all, especially the most affected.

By combining data with a human-centered approach, this project emphasizes the importance of using science to solve real problems and create positive change.

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Data Sources

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2. U.S. Environmental Protection Agency's (EPA) Air Quality System (AQS) API
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