Assessing the Regional Impact of Biomass Burning on Air Quality in the Western United States (2010 - 2023)

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ABSTRACT: This study investigates the influence of biomass burning across the Western US, utilizing satellite data from NOAA's Hazard Mapping System (HMS) to monitor smoke activities from 2010 to 2023. Routine monitoring data from Clean Air Status and Trends (CASTNET) and Interagency Monitoring of Protected Visual Environments (IMPROVE) will be used to explore trends in tracers in ambient particulate matter over time and its relationship between smoke plumes. Regression analysis of smoke frequency at 18 CASTNET and 57 IMPROVE western sites, revealed that 94.4% of CASTNET sites and 86.0% of IMPROVE sites exhibit significant upward trends in smoke activity, with the most robust signals observed in the "Light" smoke density category. Several mid-western sites for both CASTNET and IMPROVE showed increasing significance throughout all smoke density categories. Elevated levels of particulate chemistry and gaseous pollutants associated with biomass burning further highlight the regional air quality implications. To identify key elements affected by smoke events, multiple methods were used to create a ranking system. The ranking system used parameters from Spearman's correlation, Welch's Two Sample T-Test, and logistic regression. The final mean rank value along with bootstrap derived confidence intervals were used to identify analytes most likely to be affected by smoke events. Results consistently illustrated that Potassium (K), Calcium (Ca), Magnesium (Mg), and Ammonium (NH4) at CASTNET sites, along with PM2.5, Organic Carbon (OC), PM10, Total Carbon (TC), and Potassium (K) at IMPROVE sites, serve as reliable indicators of biomass burning episodes. Overall, these findings highlight the escalating regional impact of biomass burning over the past decade, underscoring the importance of fire management and air quality mitigation strategies.

BACKGROUND:
Wildfire activity in the western United States has increased substantially since the 1980s, with researchers documenting more frequent large fires, longer fire seasons, and greater burned area (Westerling et al., 2006; Abatzoglou & Williams, 2016; Parks & Abatzoglou, 2020). As wildfire activity has increased, smoke emissions have become an increasingly important source of atmospheric particulate matter and deposited pollutants across the region. Despite this growing influence, the long-term contribution of wildfire smoke to atmospheric deposition has not been rigorously evaluated, especially long term. This study addresses this gap through establishing a smoke metric dataset to address long-term analysis of smoke plume occurrence and its relation to atmospheric deposition.

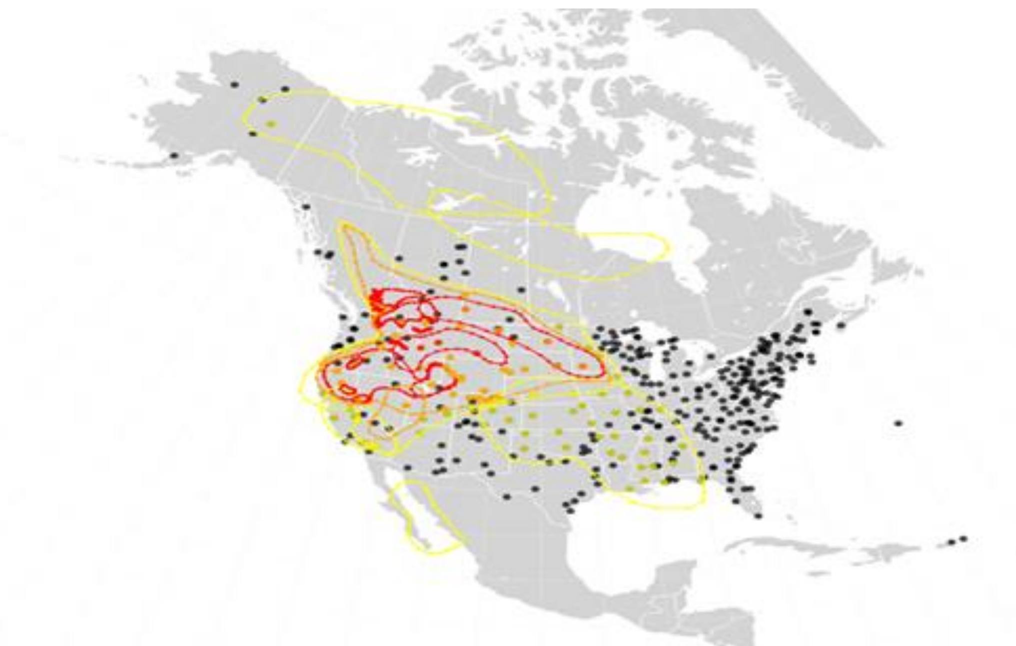

Figure 1: Smoke Events Across NTN network 7/25/2021

DATA:
CASTNET data consists of weekly concentrations of valid atmospheric pollutant deposition data. IMPROVE data consist of daily concentrations of valid atmospheric pollutant deposition data, particulate matter, and various metals.

SMOKE METRIC: HMS data is discontinuous in the daytime and does not provide nighttime imagery. Figure 1 is an example that illustrates smoke events for one day encompassing National Trends Network (NTN) sites across the US.

- Smoke intensity ~ 3 categories (Light, Medium, and Heavy)
- Three different geostationary satellites, transitioning from GOES to GOES_W, GOES_E in 2017.
- To address these aspects, each day will be assigned a single smoke density metric representing the highest density recorded for that day.
- Depending on the highest density provided in the 24-hour period, a metric of 0 (no smoke), 1 (light), 2 (medium), and 3 (high) will be assigned.
- This daily metric will then be aggregated to the corresponding time interval integrated weekly for CASTNET samples and matched with the 24-hour IMPROVE samples.
  - **DSS** - Days of sample period with smoke.
  - **FSS** (weekly samples)/**NSS** (daily samples) - Fraction of sample period in which smoke was observed.
  - **FSS_(L,M,H)** (weekly samples) **NSS_ (L,M,H)** (daily samples)- Fraction of FSS/NSS corresponding to Light, Medium, Heavy smoke density.
  - **ASDM** (weekly samples)/**MSDM** (daily samples) – Summed daily smoke density for weekly sample periods and max daily smoke metric for daily samples.

Frequency of smoke occurrences

METHODS:
- A daily smoke event table includes the date a smoke event occurred, the site id located within the geometry of a smoke plume, organization, satellite, max smoke metric (1,2,3), and total smoke events for that day. Creating this table involved matching each smoke event with a given start date in the NOAA HMS satellite dataset to the site's coordinates, see Figure 2.
- DSS for CASTNET and NSS for IMPROVE sites were summed annually for fire season months, May – October.
- Linear regression results saved for each site. These results were summarized to assess the percentage of sites with a statistically significant increasing trend. A p-value less than 5% and a positive slope provided enough evidence that the smoke occurrences for that period, are increasing.

RESULTS:
- Figures 3 and 4 illustrate each site's estimated slope for DSS and NSS smoke metrics. Table 1 summarizes the percentage of sites illustrating significant increasing trends of selected smoke metrics.
- Table 1 illustrates the main smoke frequency metrics (DSS/NSS), 94.4% (CASTNET) and 86% (IMPROVE) of sites show statistically significant upward trends and trends are strongest for "Light" density.
- For "Medium" and "Heavy" density categories, fewer sites show significant trends. Sites in the mid-west show a large significant increase in all smoke densities by year for both CASTNET and IMPROVE sites.

Evidence of biomass burning in PM Chemistry

METHODS:
- A ranking system was created using 3 methods. The first method used was **Spearman's Correlation method,** this was done on each analyte and the weekly/daily (ASDM, MSDM) smoke metric. **Welch's Two Sample T-Test** was the second method used to determine significant differences between the averages of analytes affected by smoke and not affected by smoke. **Single Logistic Regression** was the last method used; this method predicts the probability that the data set of a selected analyte concentration is indeed impacted by smoke. The rank was based on the variable importance value calculated based on the p-value given. Using the variable of importance sorted from greatest to least, a rank was assigned to each analyte for every site.
- **The Final Rank** for each method was then summed up for each analyte by site. The ranks for each analyte for all sites were summed providing the final rank value. The **error bars** show estimated uncertainty (95% confidence intervals) based on repeated resampling using bootstrap analysis.

RESULTS:
- Among the analytes evaluated in Figure 5, K demonstrated the highest mean total rank with bootstrap-derived confidence intervals, indicating it is the most robust and consistent marker for distinguishing smoke impacted chemistry. Ca and Mg also ranked highly, with moderate uncertainty, suggesting they are generally affected although with somewhat greater variability across resampling iterations than K. NH4 and SO4 displayed intermediate mean ranks and broader confidence intervals, signifying a moderate and less stable discriminatory ability.
- Figure 6 highlights OC, PM2.5, PM10 and smoke tracers such as K and Elemental Carbon (EC) as the most robust indicators of wildfire smoke events at IMPROVE sites. The high scores and relatively tight uncertainty bounds emphasize their reliability. In contrast, analytes such as Arsenic (As), Lead (Pb), Vanadium (V) and Sodium (Na) consistently rank lowest, suggesting little value as smoke markers. The moderate to high overlap among middle ranked analytes are less definitive.

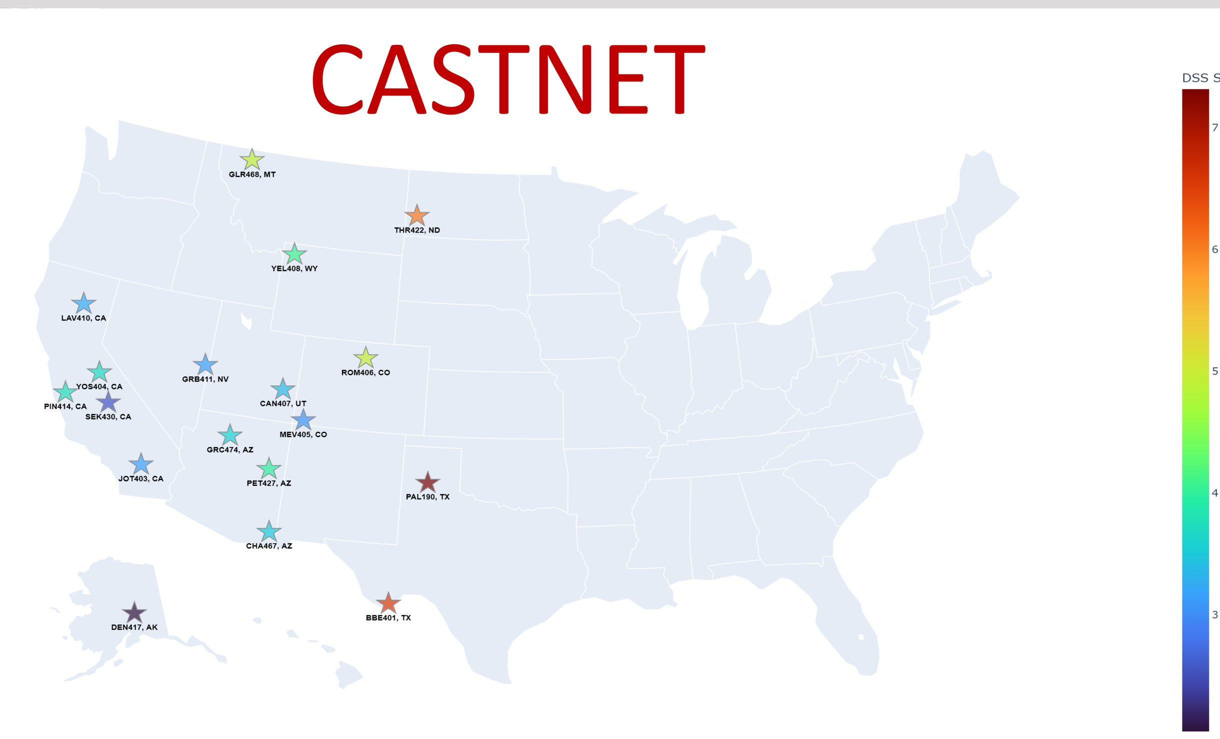

Figure 3. Estimated Slope for DSS
Note: Significance is not illustrated

Figure 4. Estimated Slope for NSS
Note: Significance is not illustrated

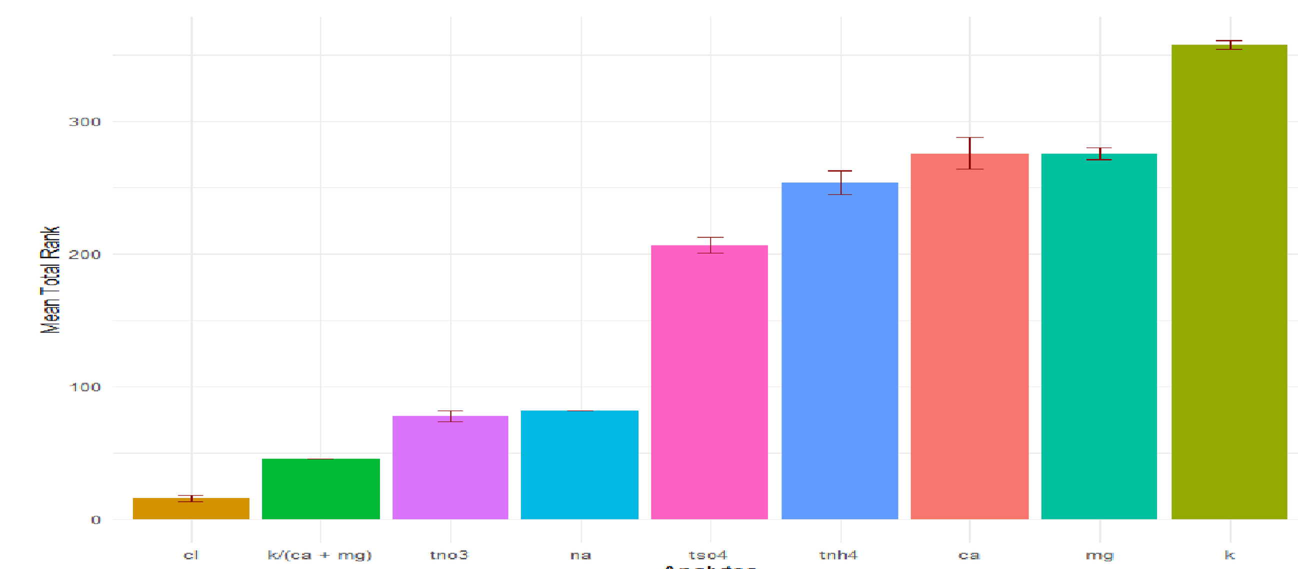

Figure 5. Final Analyte Rank

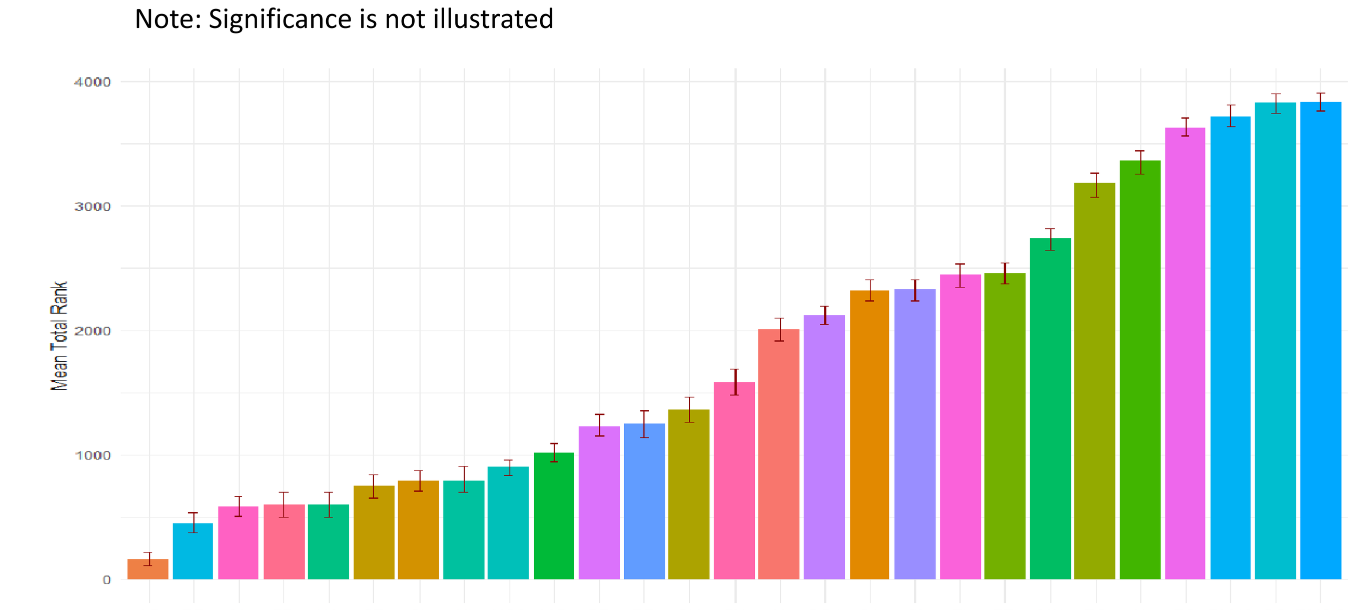

Figure 6. Final Analyte Rank

Figure 2: Smoke Plume for CASTNET (NEC602) on 9/7/2021

	DSS/NSS	FSSL/NSSL	FSSM/NSSM	FSSH/NSSH
CASTNET	94.4%	77.8%	16.7%	11.1%
IMPROVE	86.0%	96.5%	29.9%	29.9%

Table 1. Percentage of sites with significant increasing trend.

DISCUSSION :
Future work will include incorporating NTN precipitation chemistry data, continuously loading smoke data to build the smoke product data set for future long-term analysis, and developing logistic regression models for each high-ranking analyte to be used on future datasets to estimate the probability a smoke event occurred given a concentration, and time stamp.

NEXT STEPS:
- NTN smoke metric data set + precipitation.
- Extend the ranking system to the smoke intensity categories. Using different statistical methods and a multinomial logistic regression method.
- Evaluate model performance.

REFERENCES:

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