Examining the Spatio-Temporal Dynamics of Stubble Burning and its Influence on PM2.5 in Northern India: Policy Implications and Reduction Outcomes (2018 - 2023)

Mamta Kumari,Roma Jain

Abstract

The present study conducts a comprehensive spatiotemporal analysis of the impact of stubble burning on PM2.5 concentration across Northern India from the years 2018 to 2023. The rising levels of particulate matter (PM2.5) have become a critical concern, with stubble burning emerging as a significant contributor during certain periods of the year. This research aims to elucidate the intricate relationship between stubble-burning activities and PM2.5 concentration, while concurrently evaluating the effectiveness of policy interventions designed to curtail such burning practices. Utilizing a diverse dataset encompassing MODIS VIIRS Fire Radiative Power (FRP) satellite data, CPCB air quality (AQ) data, and CAQM policy changes, the study examines the temporal patterns of stubble burning incidents and their corresponding impact on PM2.5 levels over the six years. The findings of this research contribute to a more profound understanding of the interplay between agricultural practices, environmental pollution, and policy interventions.

Introduction

The growing apprehension surrounding the deterioration of air quality and its significant consequences for public health and the environment has led to increased attention to various sources of atmospheric pollution. Among these sources, stubble burning has emerged as a notable contributor to the escalation of particulate matter (PM) levels, particularly in the northern regions of India.

Stubble burning is a traditional practice involving the controlled combustion of post-harvest crop residues to prepare fields for subsequent cultivation cycles. This practice is commonly implemented following the harvest of grains such as paddy, wheat, rice, corn, and other crops.From the farmer's point of view, burning the crop residue after harvest makes it simpler for them to immediately prepare the farmland for the following sowing (of wheat or rice). Farmers are compelled to burn the stubble directly on the field to swiftly prepare the ground for the following planting, which releases a significant amount of hazardous pollutants (Krishna et al., 2011). Lack of time between harvest and seeding the following crop is another justification for burning the stubble (Ravindra et al., 2018). It was claimed that there was an average amount of time between the harvest of rice and the seeding of wheat. The average duration between the sowing of wheat and the harvest of rice was reported to be 15 days, and the time between the sowing of rice and the harvest of wheat was substantially longer, up to roughly 46–48 days. Therefore, the farmers lack the time to manage the crop stubble effectively, especially following the harvest of the rice crop (Krishna et al., 2011). The burning process emits a vast array of particulate and gaseous pollutants such as carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), and methane (CH4), as well as particulate matter (PM10 and PM2.5), all of which are harmful to human health and the environment. According to reports, burning 63 million tonnes of crop stubble emits 3.4 million tonnes of CO, 0.1 million tonnes of NOx, 91 million tonnes of CO2, 0.6 million tonnes of CH4, and 1.2 million tonnes of PM into the atmosphere. Among the direct impacts of stubble burning is the depletion of soil nutrients (nitrogen, phosphorus, potassium, and sulfur) from the uppermost topsoil layer and a reduction in soil organic matter. This degradation of soil health leads to declines in agricultural production and productivity, creating an unsustainable cycle of soil degradation and lower crop yields (Gadde et al., 2009). Furthermore, prolonged exposure to elevated levels of PM, especially PM2.5, has been linked to a range of health risks, including respiratory and cardiovascular diseases, resulting in millions of premature deaths worldwide annually. Air pollution can cause everything from skin and eye irritation to serious neurological, cardiovascular, and respiratory disorders, including asthma, chronic obstructive pulmonary disease (COPD), bronchitis, lung capacity loss, emphysema, and cancer. It also increases death rates as a result of extended exposure to high pollution levels. The Energy and Resources Institute (2019) reported that in 2012, air pollution had led to about 5 million deaths in South Asia, around 22% of the total deaths in the region.

These challenges are particularly acute in India, where the country ranks third worldwide in the number of fire incidents associated with crop residue burning (Koppmann et al., 2010). This growing problem was highlighted in a study conducted by Jethva et al. (2018), which found that the number of fire incidents in India had doubled between 2003 and 2018.

Stubble burning has a greater influence during the rice stubble burning season because lower winter temperatures lead to a more stable atmosphere (inversion circumstances). The fact that pollutants remain in the atmosphere for longer during this winter season and that the amount of rice stubble burned is much more than that of wheat results in a harsh degree of pollution that frequently obstructs visibility. Among the states most severely affected by this severe pollution are Delhi, Uttar Pradesh (U.P), Punjab, Haryana, Bihar, and West Bengal. Notably, these states also stand as the epicenters of India's agricultural productivity. Punjab, for instance, is often recognized as the nation's primary source of grains, contributing approximately 30% of the country's grain supply.

The episodes characterized by heightened concentrations of PM2.5 have attracted significant attention due to their extensive impacts on health, climate dynamics, and the overall quality of the regional air. In recent years, the field of remote sensing technology has made significant strides, providing powerful new tools to monitor and quantify the extent of stubble-burning events. Specifically, VIIRS (Visible Infrared Imaging Radiometer Suite) satellite imagery with its high resolution, has proven effective in measuring fire hotspots. It measures fire hotspots detecting the thermal radiation emitted by fires in the infrared spectrum. VIIRS fire hotspot data is utilized in this study to identify stubble-burning activities. And CPCB (Central Pollution Control Board) is used for collecting historical data on air quality.

The primary contribution of this study unfolds along two distinct dimensions: firstly, it involves an evaluation of the spatiotemporal shifts in stubble-burning activities and the concurrent air quality changes across Punjab, Haryana, Delhi, and the northwestern parts of U.P. throughout the period from 2018 to 2023. Secondly, the study investigates the ramifications of policy alterations on the gradual reduction in the incidence of stubble burning. By concentrating our analysis on the district-level specifics of these geographical areas, we intend to extract valuable insights into the evolving trends of both air quality and stubble-burning practices over these years.

Literature Review

The literature review of our paper delves into various studies focusing on the impact of stubble burning on PM2.5 concentration and policy implications in regions of Northern India. The recurring observation across these studies is the alarming increase in PM2.5 levels due to stubble-burning activities during specific periods, which has led to severe air quality degradation and public health concerns.

Several studies have emphasized the significance of agricultural residue burning in contributing to elevated PM2.5 concentrations. Saxena et al. (2021) evaluated the influence of various pollutants such as PM10, PM2.5, NO2, and SO2 emitted during CRB on the air quality of Delhi. It noted a significant increase in pollutant concentrations during the transition from pre-burning to burning periods in both rabi and kharif seasons. PM10 and PM2.5 concentrations surpass the National Ambient Air Quality Standards (NAAQS) limits by 2–3 times, while NO2 and SO2 remain within the permissible limits. The study by Govardhan et al. (2023) conducts a detailed analysis of stubble-burning activities in 2021 using MODIS active fire count data for Punjab and Haryana. The findings of this study reveal that fire counts in these regions were the highest observed over five years (2016–2021). Furthermore, an intriguing observation emerges from the analysis: the occurrence of stubble-burning fires in 2021 exhibited a delay of approximately one week compared to those in 2016.

To quantify the impact of these fires on Delhi's air pollution, the study also employs tagged tracers for carbon monoxide (CO) and PM2.5 emissions within a regional air quality forecasting system. The model-driven approach highlights a substantial contribution of stubble-burning fires to air pollution in Delhi, particularly during October and November 2021, reaching levels of around 30–35% of daily mean pollution. Interestingly, the analysis also reveals temporal variations in the contribution of stubble-burning activities to air quality in Delhi. The contribution is shown to be at its peak during turbulent hours from late morning to afternoon, while it is relatively lower during calmer hours from evening to early morning. While this study is a comprehensive one, it has limited its study only to the year 2021. We have extended the analysis till 2023 for Punjab, Haryana, Delhi, and Northwestern parts of Uttar Pradesh. Another interesting study by Lan et al. (2022) emphasizes the far-reaching consequences of crop residue burning on air quality in Pakistan, Nepal, and Bangladesh, thereby highlighting the need for coordinated efforts to address this issue within India and neighboring countries within the South Asian region.

This study by Mohite et al. (2022) focuses on the impacts of lockdown on the concentration of various pollutants such as nitrogen oxide (NO2), carbon monoxide (CO), and aerosol optical depth (AOD) and also quantifies the contribution of crop stubble burning to air pollution. The Sentinel-5P NO2 and CO observations for 2019 and 2020 and Moderate Resolution Imaging Spectroradiometer (MODIS)-based AOD observations for 2016–2020 were used for detecting the variations. Furthermore, this study also analyzed the contribution of NO2, CO, and AOD from crop stubble burning. They reported that the burning of crop stubble increased NO2 emissions by 22 to 80%. CO levels, on the other hand, have risen by 7 to 25%. A considerable variation in AOD was reported, ranging from 1 to 426%.

While many studies focused on the technical aspects of stubble burning and its effects on air quality, this study by Kaushal (2022) aims to provide insights into the effectiveness of numerous policy interventions to curb FCRB-induced air pollution in NW India from the years 2014 to 2020. This study suggests that besides the short-term residue management measures, crop diversification or discontinuing dual rice-wheat cultivation is the only long-term measure to regulate widespread stubble burning and deteriorating air quality.

This study by Gulati et al. (2023) examined the spatial and temporal patterns of stubble-burning events and their potential effect on ambient air quality from 2019 to 2022. High-resolution Sentinel-2 satellite imagery was employed to delineate the spatial extent of stubble burning. Burnt areas were identified using the Normalised Burn Ratio (NBR). Air quality was evaluated based on PM2.5 and PM10 concentrations data obtained from the Punjab Pollution Control Board. It mentions that the smallest burnt areas were recorded in October 2019 and 2021 (209 sq km), while the largest was in 2020 (755.38 sq km). In every year studied, the burnt area in November consistently exceeded that in October, with the largest area (10315 sq km) observed in 2021. PM2.5 and PM10 concentrations also showed annual fluctuations, with the highest recorded in 2020 and 2021. In particular, in October 2020, higher PM2.5 and PM10 levels were detected in the eastern region of Punjab. November consistently exhibited higher PM2.5 and PM10 concentrations than October for all years analyzed, peaking in 2021.

Our analysis builds upon this knowledge by investigating the comprehensive spatiotemporal trends of stubble burning's influence on PM2.5 concentration across Punjab, Haryana, Delhi, and Northwestern parts of Uttar Pradesh from 2018 to 2023 along with studying the policy changes implications on a gradual reduction in stubble. The insights gained from these studies play a pivotal role in guiding evidence-based decision-making processes for air quality improvement and sustainable agricultural practices in Northern India.

Methodology

This study relied on various data sources to meticulously analyze stubble-burning events and comprehend their subsequent impact on air quality in Punjab, Haryana, Delhi, and Northwestern parts of Uttar Pradesh.

The data sources involved in this research are summarised in Table 1. To discern and monitor stubble-burning incidents, we relied on VIIRS fire hotspot satellite data, which enabled a detailed and precise identification of active fire data. To understand the after-effects of stubble burning on the air quality, we used air quality data, specifically PM2.5 concentration, derived from the Central Pollution Control Board (CPCB). Fig 2 displays CPCB monitoring stations that provide the crucial data. To understand policy implications, we referred to CAQM (Commission for Air Quality Management) policies from the years 2018 to 2023 and their implementations.

Data	Source	States
1. Fire Hotspot	MODIS/VIIRS	Punjab, Haryana, Uttar pradesh
2. Air Quality (PM 2.5)	CPCB	Delhi, Uttar pradesh, Haryana, Punjab

Table 1: Data Sources for Fire Hotspot and PM 2.5 Concentration

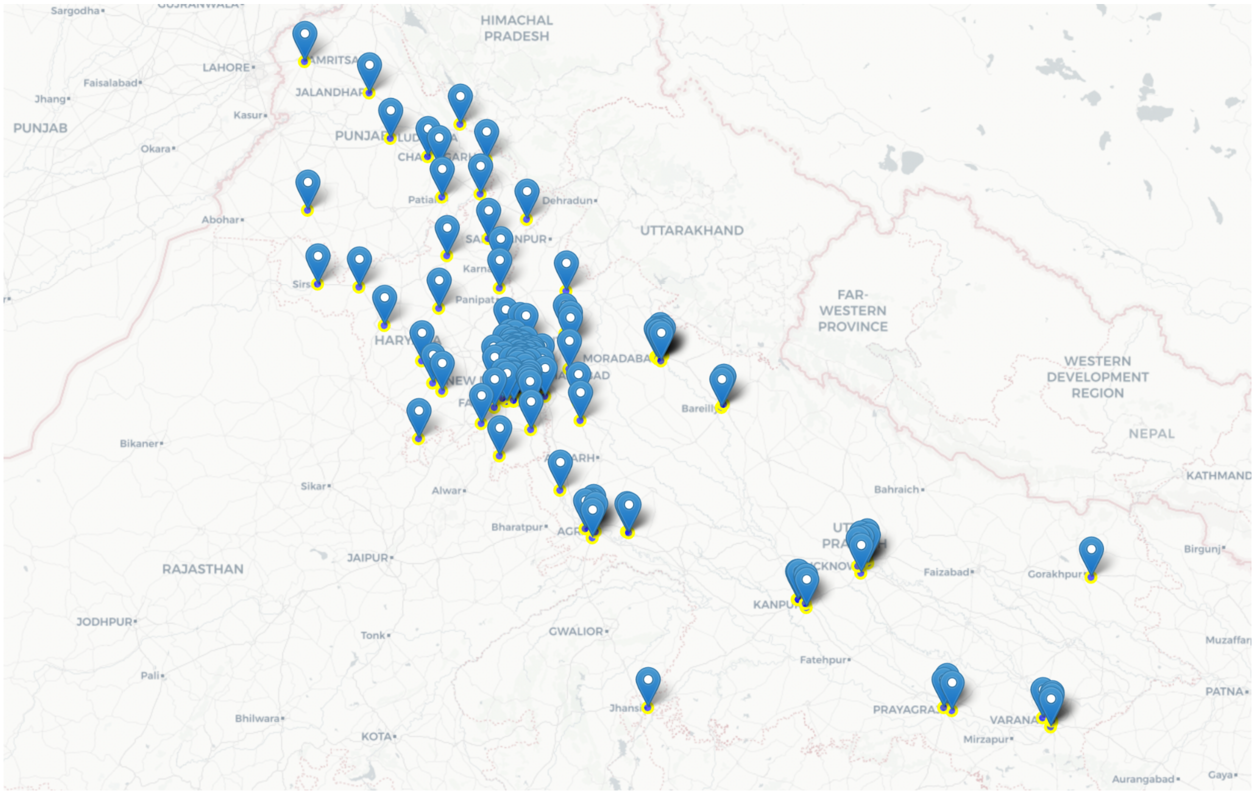


Fig 2: CPCB AQ Monitoring stations

The data used for this study, including fire incidents and air quality, was sourced from the references listed in Table 1. The dataset covers the years 2018 to 2023 and includes data from the states of Punjab, Haryana and Uttar Pradesh.

Our initial data processing steps involved data cleaning and the identification of outliers. To ensure the quality of our analysis, we treated the outliers in the fire data for variable Fire radiative Power (FRP). Outliers in this variable were capped at a maximum value of 250 MW.

Similarly, we undertook a thorough cleaning of the air quality data to eliminate outliers and fill in for the missing values. Missing values were filled using backward fill method. In the initial phase of data cleaning, we ensured that the PM2.5 concentration was consistently lower than the corresponding PM10 concentration. Additionally, to enhance data quality, we set an upper limit by capping any extreme outliers at a maximum PM2.5 concentration of 500 $\mu g/m^3$. This cleaning process was essential to enhance the accuracy of our subsequent air quality distribution map.

The primary objective of our analysis was to unveil patterns within the fire and air quality data, examining them at various temporal scales such as yearly, monthly and daily.

The first phase of the analysis involved finding yearly patterns. We calculated the total number of fire incidents attributed to stubble burning in the selected states for the years 2018 to 2023. These calculations served two key purposes, first, they offered insights into the trends of stubble burning activities over this six-year period, and second, they pinpointed the months with the highest incidence of stubble burning. The second aspect was crucial for understanding the seasonality of crop burning.

Subsequently, we wanted to dive deeper into the spatial dynamics of stubble burning. We identified the top five districts in Punjab, Haryana and Uttar Pradesh that contributed the most to stubble burning from 2018 to 2023. Our analysis also considered both the kharif and rabi crop burning seasons separately.

The second part of the first phase was to analyse the air quality data, aligning its temporal scale with that of the fire data. Our primary focus was on the distribution of PM2.5 concentration within the years 2018 to 2023. We created graphs that highlighted the monthly variations in PM2.5 concentration across these selected years using box and whisker plots. Our analysis encompassed all the states under consideration for air quality assessment, namely Punjab, Haryana, Uttar Pradesh and Delhi.

We wanted to understand the statistical aspect of the air quality distribution, so we took the months prominently polluted after kharif crop burning season which are October to December and months after rabi crop burning season which are April, may and June.

Moving on to the second phase of our analysis, we dived into the daily dynamics of air quality, particularly focusing on the maximum PM2.5 concentration. This exploration covered both the kharif burning season (15 September - 31 December) and the rabi burning season (15 March - 30 June), spanning from 2018 to 2023. Our primary objective was to find the daily maximum in PM2.5 levels based on their severity as per the Air Quality Index (AQI) standards. This allowed us to identify the specific days falling within different AQI severity levels.

We further graphed the heatmap of daily total fire counts from Punjab, Haryana and Uttar Pradesh from 2018 - 2023. This highlights the weeks and days when the stubble burning was intense in a particular year.

In understanding stubble burning behaviour, it was not enough to only rely on the count of fires occurring across the states but we also need to understand the intensity of the stubble burning, due to which we also looked into FRP(Fire Radiative Power) of the stubble burning and their pattern. We plotted the graphs representing daily maximum FRP for both the crop burning seasons.

After we looked at the FRP graphs, we wanted to understand the fire and air quality behaviour together. We plotted a merged plot of the daily maximum PM2.5 concentration and daily maximum FRP for the same time periods. The aim was to understand the effect of stubble burning on the air quality.

Our study also focused on the influence of policies designed to mitigate air pollution resulting from stubble burning. In this context, we closely examined districts where stubble burning decreased and those where it increased. From this district level analysis, we aimed to provide insights into how effective measures have been in addressing the issue of stubble burning and its associated air pollution.

Study of Policies and Their Implications

This section provides an overview of different policies that have been introduced to deal with the issue of stubble burning. It also presents the outcomes that were desired to be fulfilled by these policies and an evaluation of what has been achieved to date.

Given that there are benefits and disadvantages related to the practice of stubble burning, the government has been laying down policies to manage it effectively.

The positive impacts of Stubble Burning are:

1. Mitigation of nitrogen tie-up concerns.
2. Effective control measures against pests such as termites and slugs.
3. Eradication of weeds, including those displaying resistance to herbicides.
4. An economically viable and swift means of field clearance.

However, it should be noted that the retention of stubble can elevate the risk of stubble-borne diseases, which mandates a proactive and holistic approach to disease management. This entails the selection of disease-resistant crop varieties, the implementation of inter-row sowing practices, crop rotation strategies, and the judicious use of strategic fungicides to govern disease occurrences. Although burning can curtail disease levels, it only affords partial control, with certain residual disease factors persisting, such as crown rot, take-all, and other fungal ailments.

The ill effects of stubble burning are listed below

1. Heightened instances of pests or termites due to the annihilation of beneficial microorganisms.
2. Depletion of vital nutrients (such as nitrogen, sulfur, phosphorus, organic carbon, and potassium) that could otherwise be repurposed for organic manure.

3. Impairment of soil fertility, resulting in a diminished capacity for nutrient retention.
4. Loss of soil moisture, coupled with the disruption of beneficial microbial activity.
5. Emission of hazardous pollutants into the atmosphere, encompassing carbon monoxide, methane, volatile organic compounds, and carcinogenic polycyclic aromatic hydrocarbons.
6. Incomplete elimination of below-ground inoculum, exacerbating diseases such as crown rot and take-all.

Based on a broad framework developed by the Commission and learnings from the past paddy harvesting seasons, a comprehensive Action Plan was prepared by the State Government of Punjab, with the following major pillars of action:

1. Diversification to other crops, diversification to low straw generating and early maturing paddy varieties;
2. In-situ crop residue management including bio-decomposer application;
3. Ex-situ crop residue management;
4. IEC (Informations, Educations, and Communications) activities;
5. Monitoring and effective enforcement.

Several policies and initiatives have acknowledged the significance of paddy straw utilization. Both state and national policies, including the 'New and Renewable Energy Sources' policy (2012), the 'Biomass utilization through co-firing in pulverized coal-fired boilers' policy (2018), and the 'National Policy on Biofuels' (2018), have been formulated with the aim of harnessing residual straw for power generation, biofuel production, and related applications. These programs hold the potential to mitigate crop residue burning and reduce greenhouse gas emissions. However, several challenges pose obstacles to the seamless utilization of paddy straw.

The initial step in establishing an effective and appealing energy production system is the collection of straw. However, the advent of combine harvesters has presented a significant hurdle to rice straw collection, leading to bottlenecks in the rice straw supply chain (Balingbing et al., 2020). Recognizing the limited manpower and narrow timeframe available for straw collection, the use of balers has emerged as the most viable and cost-effective option. Nevertheless, the scarcity of storage facilities has emerged as a major concern. The surplus supply exceeding demand complicates the centralized storage of all collected stubble, and the situation intensifies due to the necessity of collecting stubble within a specified timeframe. Prolonged storage of biomass material adversely affects straw quality since moisture content cannot be adequately controlled, potentially causing complications in plant technologies (Rentizelas et al., 2009). The scarcity of storage facilities, coupled with high storage costs and procurement delays, leads to post-harvest wastage of wheat and rice, ultimately affecting the overall feasibility of biomass enterprises.

In response to the fiscal year 2018 budget, a Central Sector Scheme titled 'Promotion of Agricultural Mechanization for In-Situ Management of Crop Residue' was introduced in states such as Punjab, Haryana, Uttar Pradesh, and the National Capital Territory of Delhi, spanning the period from 2018-19 to 2019-20. This initiative, jointly implemented by the Government of India and the state governments of Punjab and Haryana, aimed to position Crop Residue Management (CRM) machinery in fields before paddy harvesting, ensuring its availability to farmers for subsequent wheat sowing. The scheme offered higher subsidies to farmers for the acquisition of a range of machinery dedicated to in-situ crop residue management. The most widely promoted machine under government sponsorship, the Happy Seeder, has witnessed a sharp decline in distribution due to several factors:

1. In Punjab, the majority of available tractors possess a horsepower capacity of 30-40, insufficient for effectively operating the Happy Seeder machine, which requires tractors with a capacity of 65 horsepower or more (Kumar, 2019). Consequently, this situation places added pressure on farmers to hire tractors capable of handling the Happy Seeder, even though government subsidies are available for these machines. This circumstance renders such initiatives economically unviable, especially for small and marginal farmers.
2. The Happy Seeder, being utilized for only 20-25 days each year, is not perceived as a worthwhile investment by farmers, leading to prolonged periods of inactivity.
3. Certain Happy Seeder machines have encountered operational issues, and the lack of adequate after-sales support from vendors has left farmers with no recourse but to revert to traditional crop burning and sowing methods.
4. Limitations of the Happy Seeder include its inability to till land beyond 8 acres per day, resulting in delays in wheat sowing.

The supply-demand gap for in-situ machinery further pressures farmers to resort to stubble burning, given the limited number of suppliers and the inability to meet the substantial equipment demand within a constrained timeframe. Despite subsidies, farmers are required to pay an additional ₹25,000 for the acquisition of a super seeder. Furthermore, delays in monsoon withdrawal shorten the window available for field preparation before wheat sowing, which typically occurs in the first half of November.

Composting, a natural process involving the decomposition of organic matter by microorganisms (Misra et al., 2003), presents a promising solution for managing paddy residues. Although composting has long been employed for domestic waste management, it is gaining prominence within the agricultural sector (Bhuvaneshwari et al., 2019). Paddy residues, rich in organic content, render them ideal for composting, similar to manure and food waste. Composting offers the advantage of replenishing soil with essential nutrients while fostering sustainability by recycling organic matter back into the soil. Research on bio-composting conducted in Uttar Pradesh by Singh and Prabha (2018) has demonstrated a significant enhancement in the agronomic properties of rice and wheat crops. Compost-amended soil, abundant in carbon and organic matter, not only boosts yield but also enhances resistance to external factors such as drought, disease, and toxicity. Given the escalating impact of climate change on agriculture in this region, composting merits careful consideration.

It is noteworthy that the economic challenges associated with domestic composting differ from those of agricultural composting. While domestic/municipal composting end products often encounter difficulties in securing a stable market, this issue does not apply to agricultural composting. In agricultural contexts, on-site compost can be readily incorporated back into the same agricultural lands (Misra et al., 2003; Shilev et al., 2007). Additionally, a new product, the 'Pusa decomposer,' developed by the Indian Agricultural Research Institute (IARI) in New Delhi, offers an effective and rapid solution for stubble management. When applied to standing stubble, this solution decomposes it within 25 days, a significant improvement compared to alternative methods requiring three months.

The over-reliance on paddy and wheat has led to various socio-economic as well as environmental concerns such as groundwater depletion, decline in soil fertility, rise in water pollution due to over-usage of chemicals, and soil erosion. Programs like ‘Crop Diversification (2013)’ which aim to diversify the land under paddy to other crops were introduced in the hope that the farmers will shift from the monoculture. Despite the government's concerted efforts to encourage crop diversification, rice and wheat continue to dominate agricultural land usage over other crops. Several factors contribute to the program's perceived ineffectiveness:

1. The program articulates objectives related to soil health improvement, groundwater conservation, and enhanced farm income. However, it lacks a clear roadmap for realizing these goals. The absence of well-established market linkages for alternative crops, coupled with the existing robust market support for paddy cultivation, presents economic challenges that deter farmers from transitioning to other crops. This overreliance on paddy and wheat cultivation has given rise to a host of socio-economic and environmental concerns.
2. The persistent prevalence of incentives predominantly directed toward paddy and wheat cultivation naturally steers farmers toward practices that yield greater profitability and higher net returns. The advantages offered by paddy and wheat, including shorter growth cycles compared to alternative crops, indicate a disconnect in translating policy objectives into successful outcomes. The escalating instances of stubble burning and associated pollution crises demand urgent attention. While the introduction of improved rice varieties with shorter maturation periods (approximately 125 days) appears promising for curbing burning practices, the promotion of these new varieties may inadvertently hinder efforts to achieve the desired outcomes of the crop diversification program. The program's oversight of issues pertaining to the storage and transportation of alternative crops presents a substantial gap. Attention should be directed toward the development of essential infrastructure, including agro-processing units and cold storage facilities.
3. Furthermore, the honorarium provided under the scheme falls short of incentivizing farmers to sustain diversification efforts. The incentives favoring rice and wheat cultivation outweigh those available for alternative crops.
4. Despite active government promotion of crop diversification programs, the financial support extended inadvertently obstructs diversification. This is evident in the significant decline—97% in the allocation of funds—observed in the

2018-19 budget allocation compared to the 2013-14 Figs. The paucity of funds and adequate government support has dissuaded farmers from embracing experimentation, particularly small and marginal farmers who face financial constraints.

5. The funding mechanism, reliant on the Centre-State formula, presents a major impediment to addressing fund inadequacy. With the Centre contributing 60% and the state responsible for the remaining 40%, the limited fiscal capacity of state governments often hinders fund allocation, as the Centre withholds its share until the state fulfills its financial commitment (Chaba, 2020b).

Results

After an in depth study of stubble burning and its impact on air quality we found some important results.

We looked at the combined monthly count of fires from 2018 to 2023 in Punjab, Haryana and Uttar Pradesh, as shown in Fig 3. We also examined the individual fire counts in each of these states, which we can see in Figs 4 to Fig 6. This comprehensive approach helped us assess how significant stubble burning is both regionally and within each state.

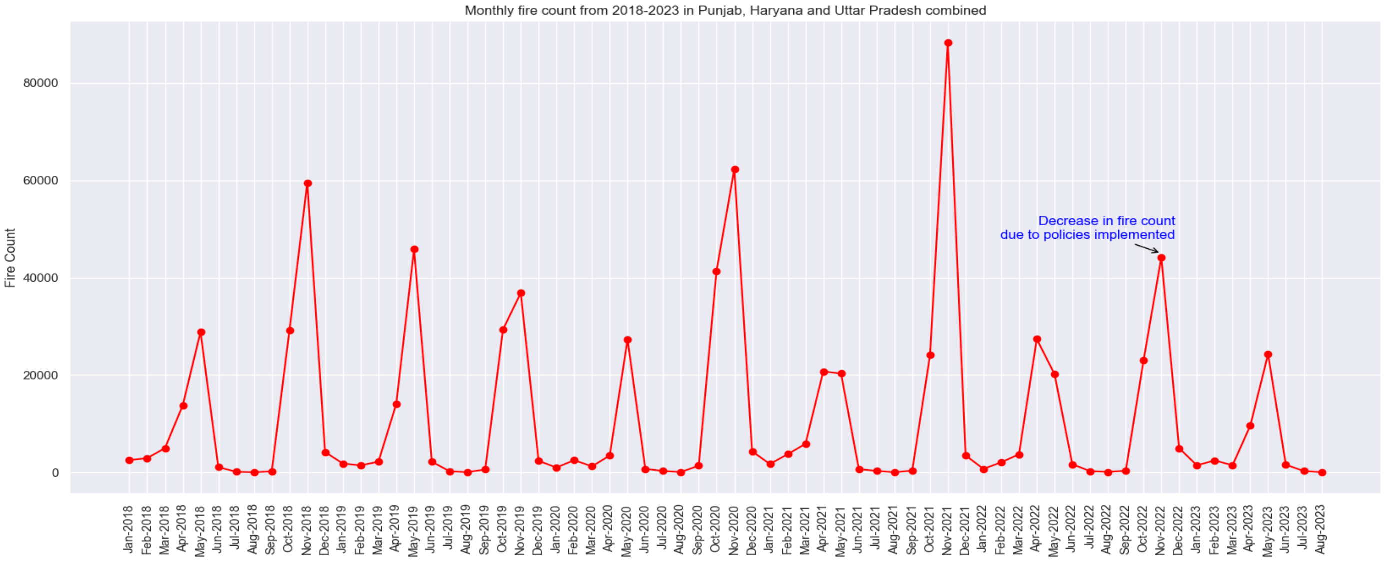


Fig 3: Monthly count of fire from 2018-2023 in Punjab, Haryana and UP combined

In Fig 3, we can clearly observe the fire count spike in May and November of every year from 2018-2023 due to rabi crop burning in May and kharif crop burning in November.

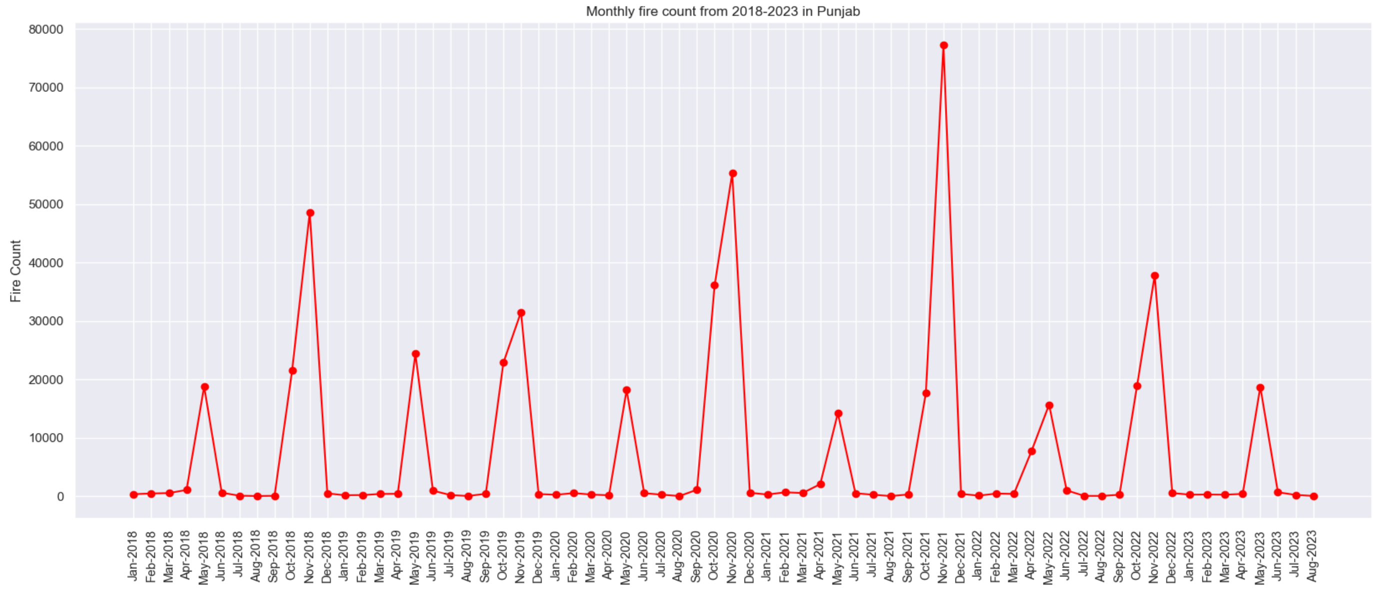


Fig 4: Monthly count of fire from 2018-2023 in Punjab

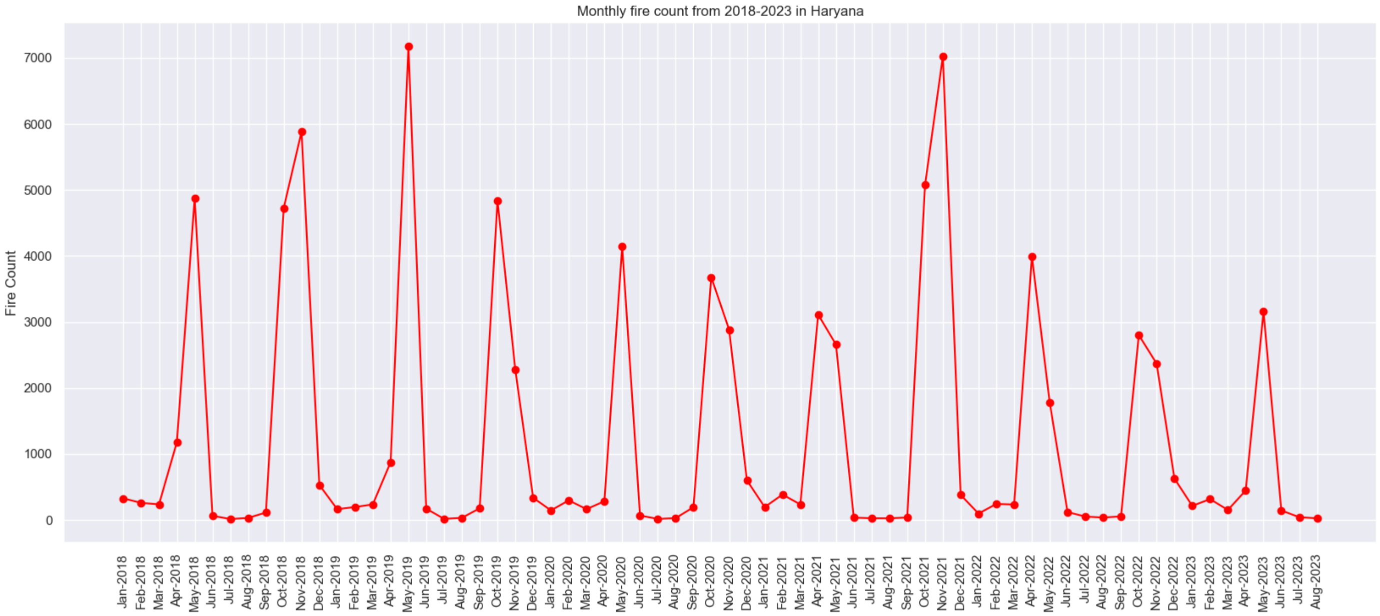


Fig 5: Monthly count of fire from 2018-2023 in Haryana

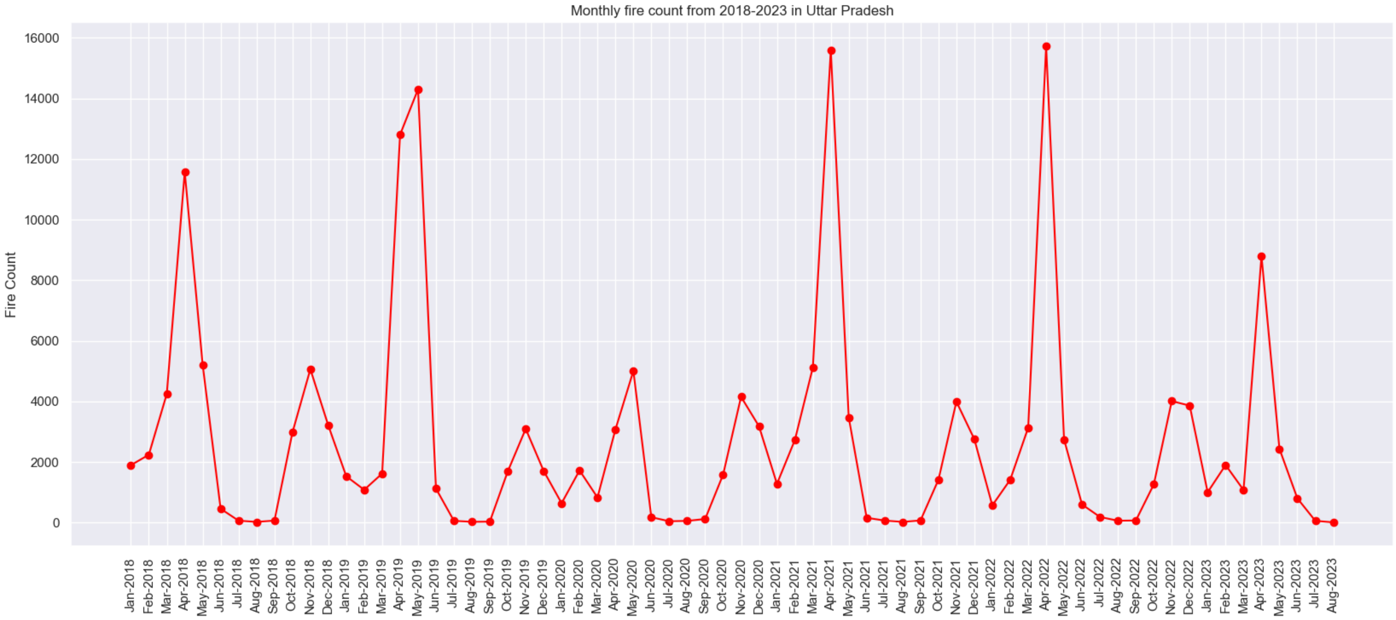


Fig 6: Monthly count of fire from 2018-2023 in UP

We observed that there are more stubble burning in Uttar Pradesh during April and May compared to October and November.

Additionally, in 2021, Punjab had the highest number of fires among the years 2018 to 2022, with 95754 instances.This was a 35.2% increase from 2018. However in 2022, there were 57461 fires, which was a decrease of 39.9% from the previous year due to various policies implemented to reduce stubble burning. We have also shown a table representing the total number of fire activities in Punjab, Haryana and Uttar Pradesh in the years 2018 - 2023. Table 2 represents the kharif crop burning season from 15 September to 30 November and Table 3 represents the rabi crop burning season from 15 March to 31 May.

Year	**Punjab**	**Haryana**	**Uttar Pradesh**
2018	70675	11239	11287
2019	55106	7605	6503
2020	93048	7334	9006
2021	95574	12508	8209
2022	57461	5821	9176

Table 2: Total Number of fire activities after kharif crop season

Year	**Punjab**	**Haryana**	**Uttar Pradesh**
2018	20139	6185	19852
2019	24992	8187	28151
2020	18482	4511	8565
2021	16508	5876	22868
2022	23535	5898	20920
2023	19174	3675	11597

Table 3: Total Number of fire activities after rabi crop season

To understand stubble burning better, we looked closely at how fires are spread across different districts in Punjab, Haryana and Uttar Pradesh during both the kharif and rabi crop burning periods. Our aim was to pinpoint which districts had the most fires during these agricultural seasons. We've summarized the results in Figs 7 to 12, highlighting the top five districts in each state for both the kharif (15 September - 30 November) and rabi (15 March - 31 May) crop burning seasons. This helps us see how stubble burning is distributed in specific regions within each state, giving us a clearer picture of this phenomenon at a local level.

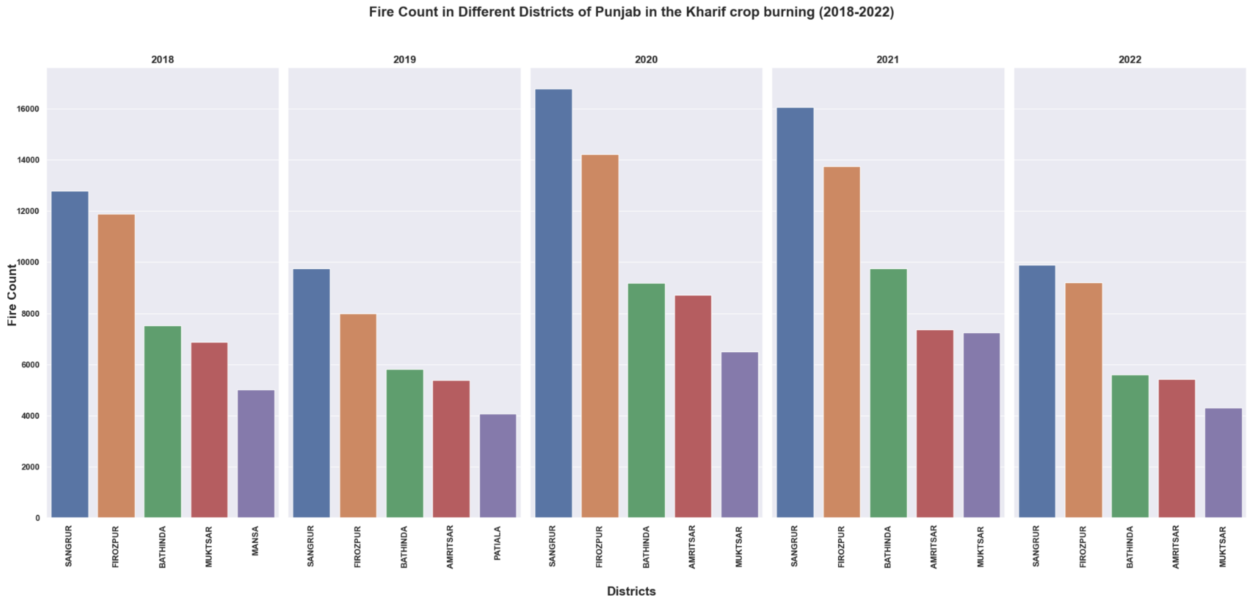


Fig 7: Fire count in different districts of Punjab in the kharif crop burning (2018-2022)

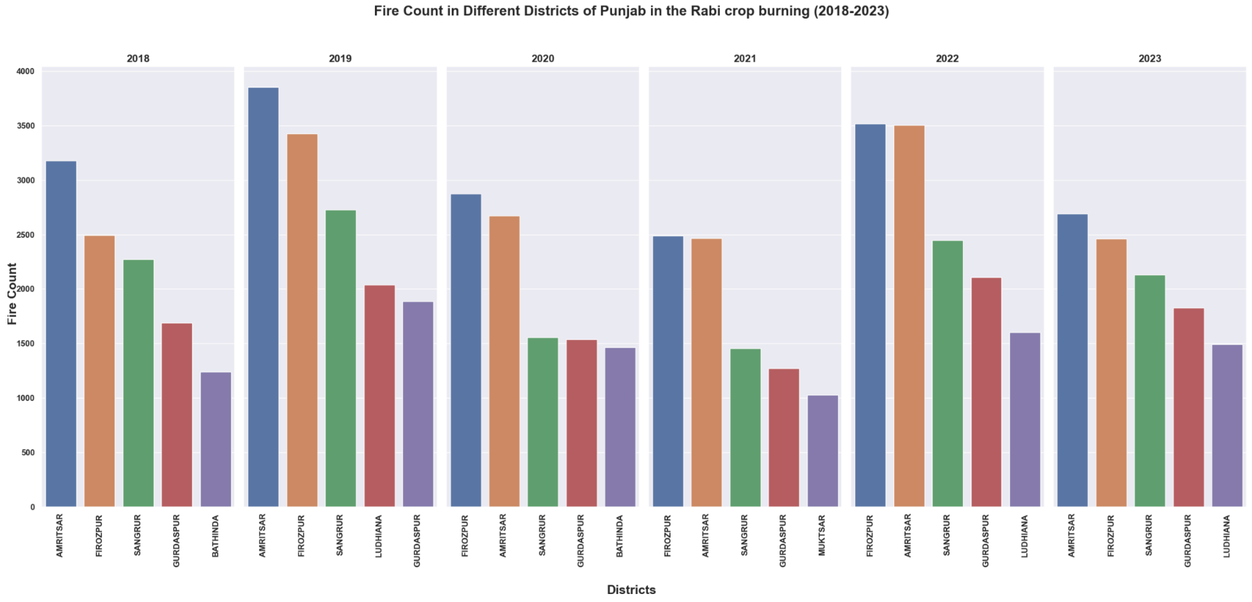


Fig 8: Fire count in different districts of Punjab in the rabi crop burning (2018-2023)

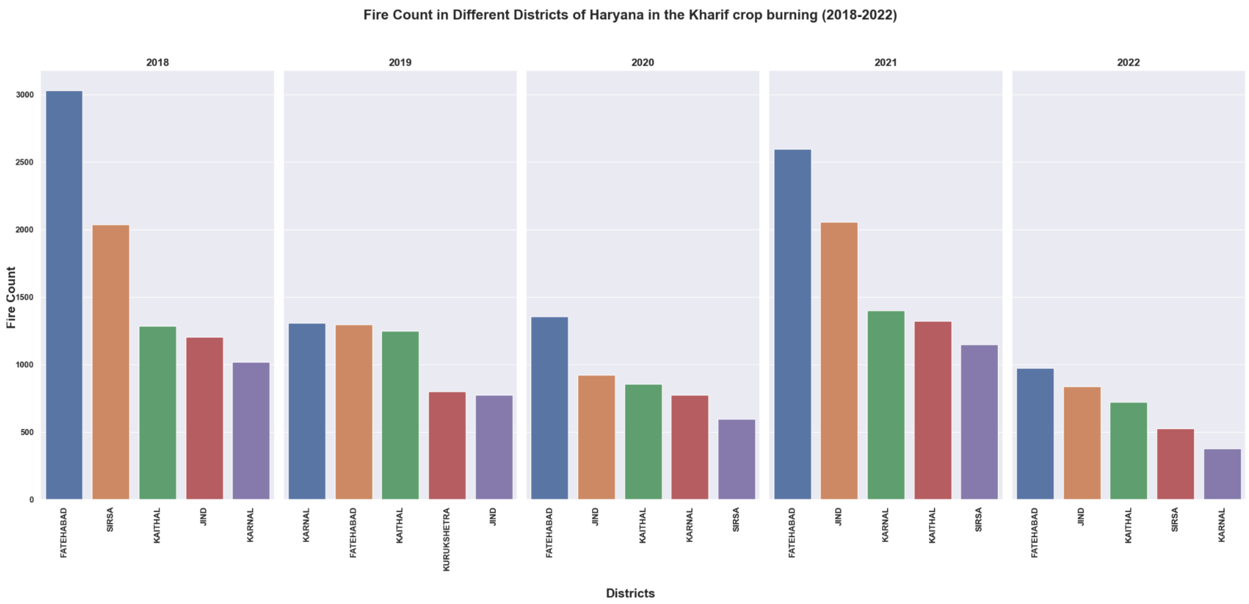


Fig 9: Fire count in different districts of Haryana in the kharif crop burning (2018-2022)

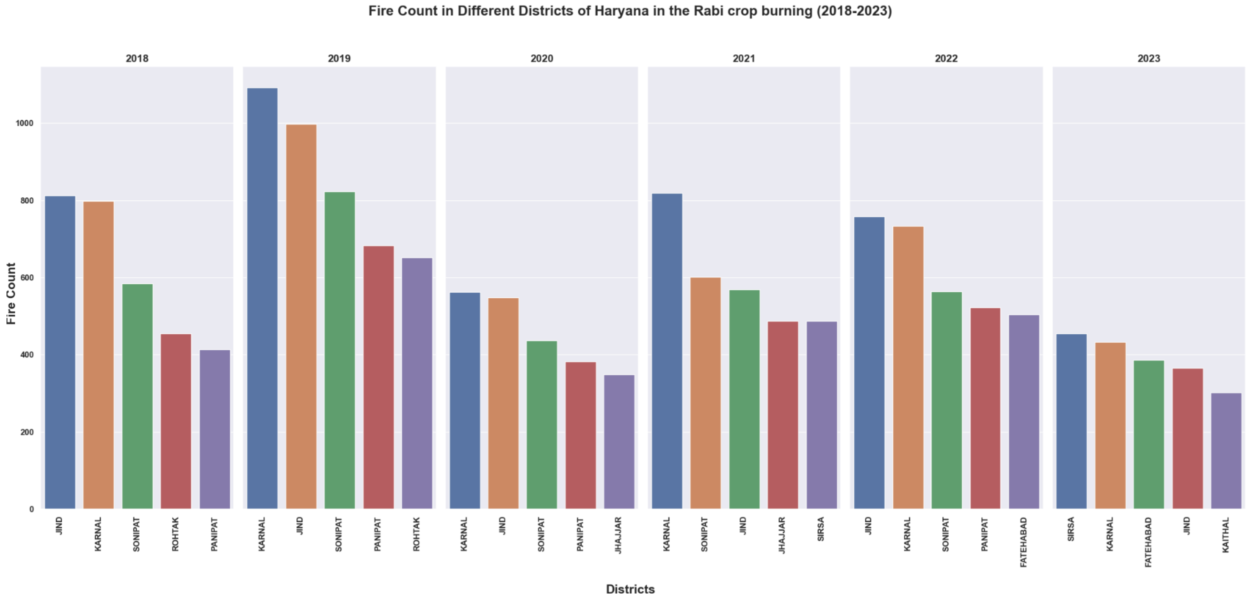


Fig 10: Fire count in different districts of Haryana in the rabi crop burning (2018-2023)

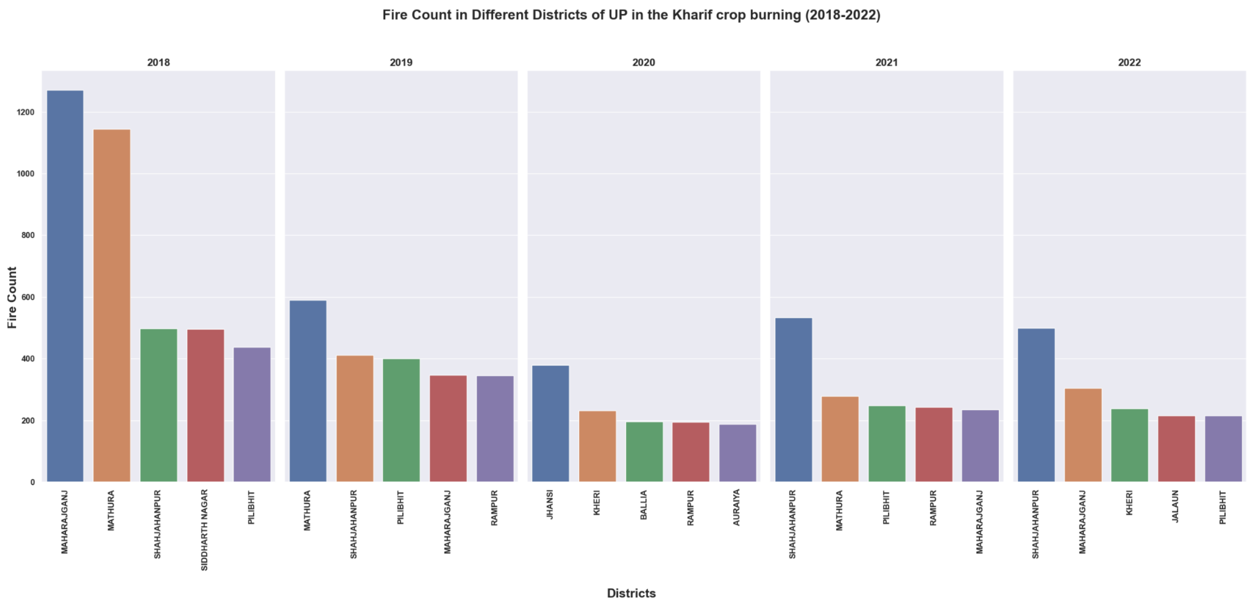


Fig 11: Fire count in different districts of Uttar Pradesh in the kharif crop burning (2018-2022)

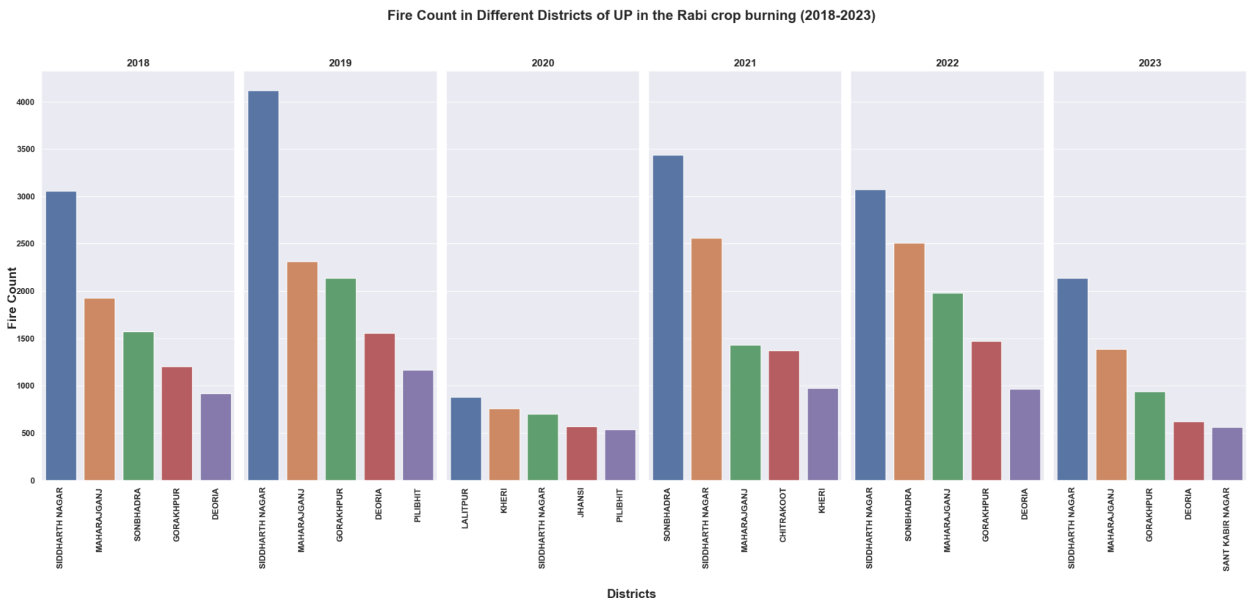


Fig 12: Fire count in different districts of Uttar Pradesh in the rabi crop burning (2018-2023)

During both the kharif and rabi crop burning seasons, we discovered that Punjab, Sangrur, Firozpur and Bathinda had the highest number of fire incidents. In Haryana, it was Fatehabad, Karnal, Kaithal and Jind that topped the list for stubble burning. In Uttar Pradesh, the districts with the highest fire occurrences were Maharajganj, Mathura, Shahjahanpur and Pilbhit.

After carefully looking at the stubble burning data we then tried to understand the PM2.5 distribution patterns caused due to stubble burning.

The air quality distribution map represents the distribution of PM2.5 in a single month. This depiction is inclusive of data from all air quality monitoring stations within the respective state. Additionally, the plot also highlights the maximum PM2.5 concentration recorded within that specific month. The air quality distribution map was constructed for all states under consideration in Fig 13, Fig 14, Fig 15 and Fig 16. The plot, covering 2018 to 2023, helps us see how PM2.5 levels change over time.

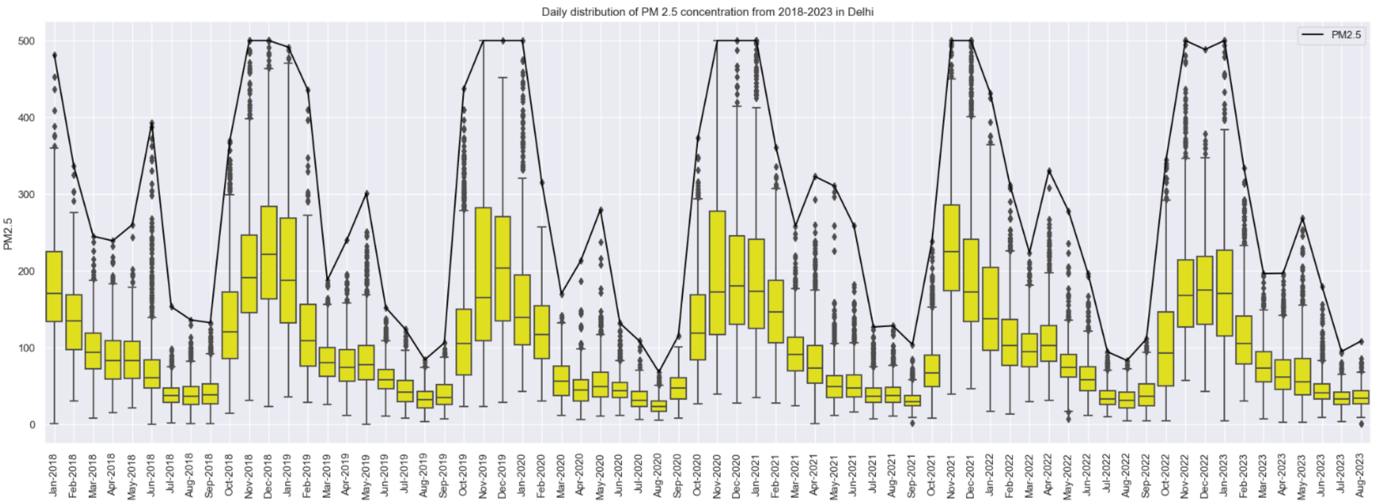


Fig 13: Distribution of PM2.5 from 2018-2023 in Delhi

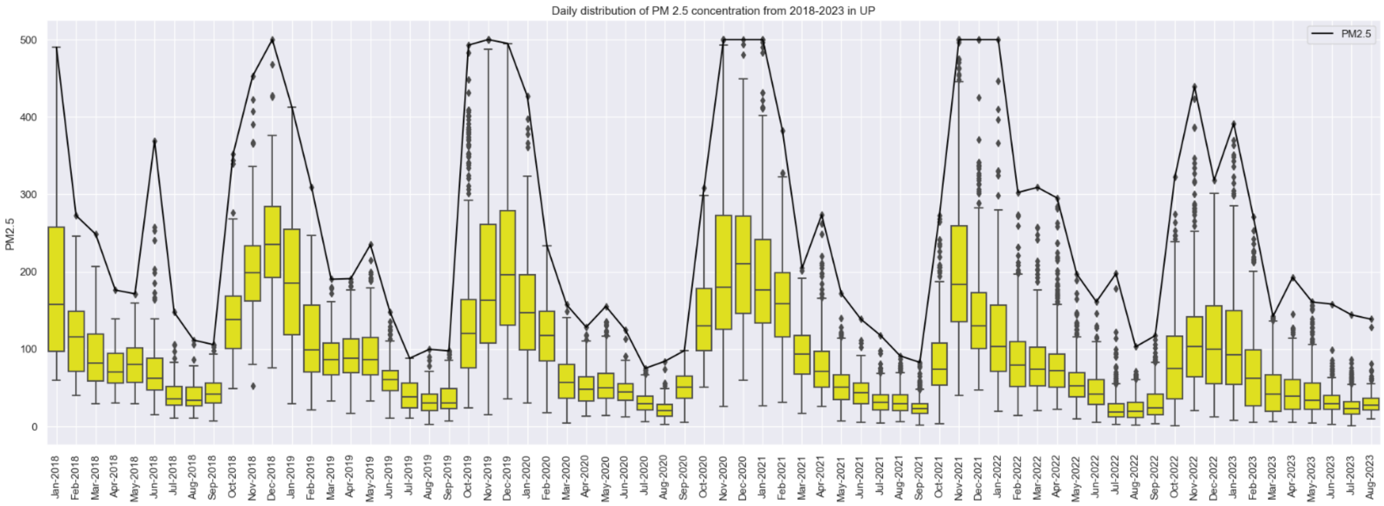


Fig 14: Distribution of PM2.5 from 2018-2023 in UP

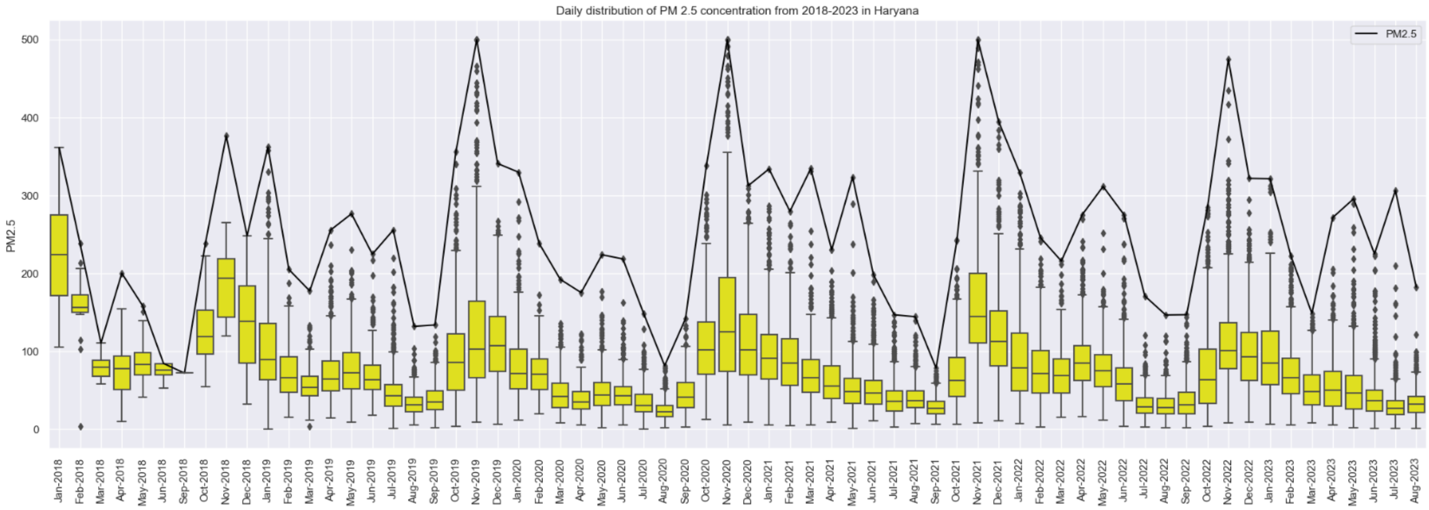


Fig 15: Distribution of PM2.5 from 2018-2023 in Haryana

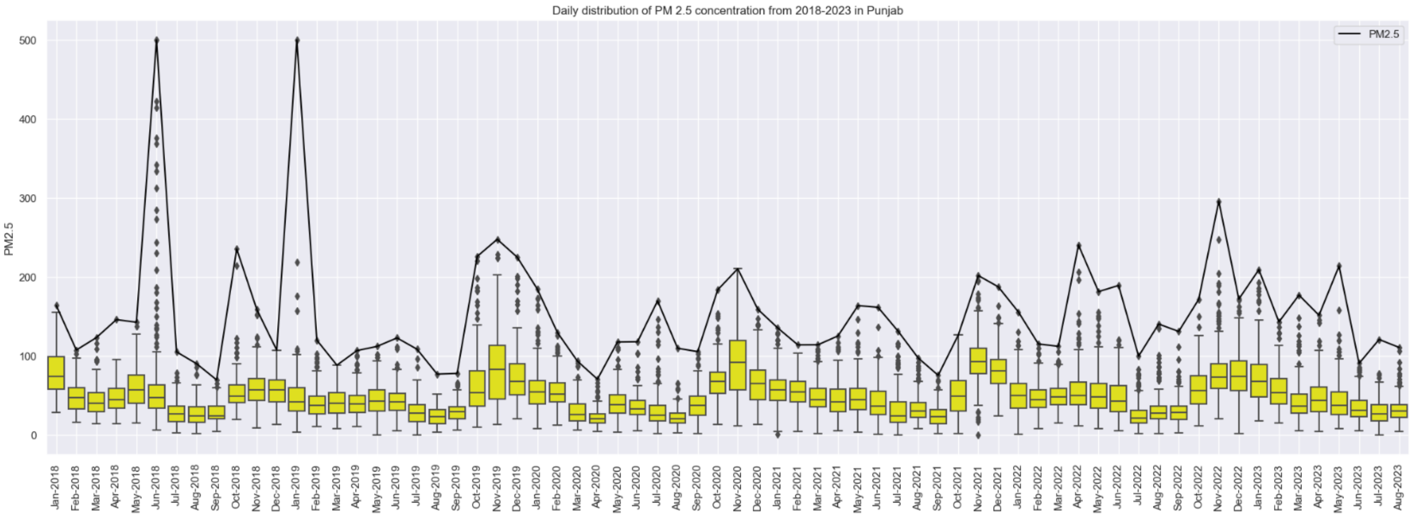


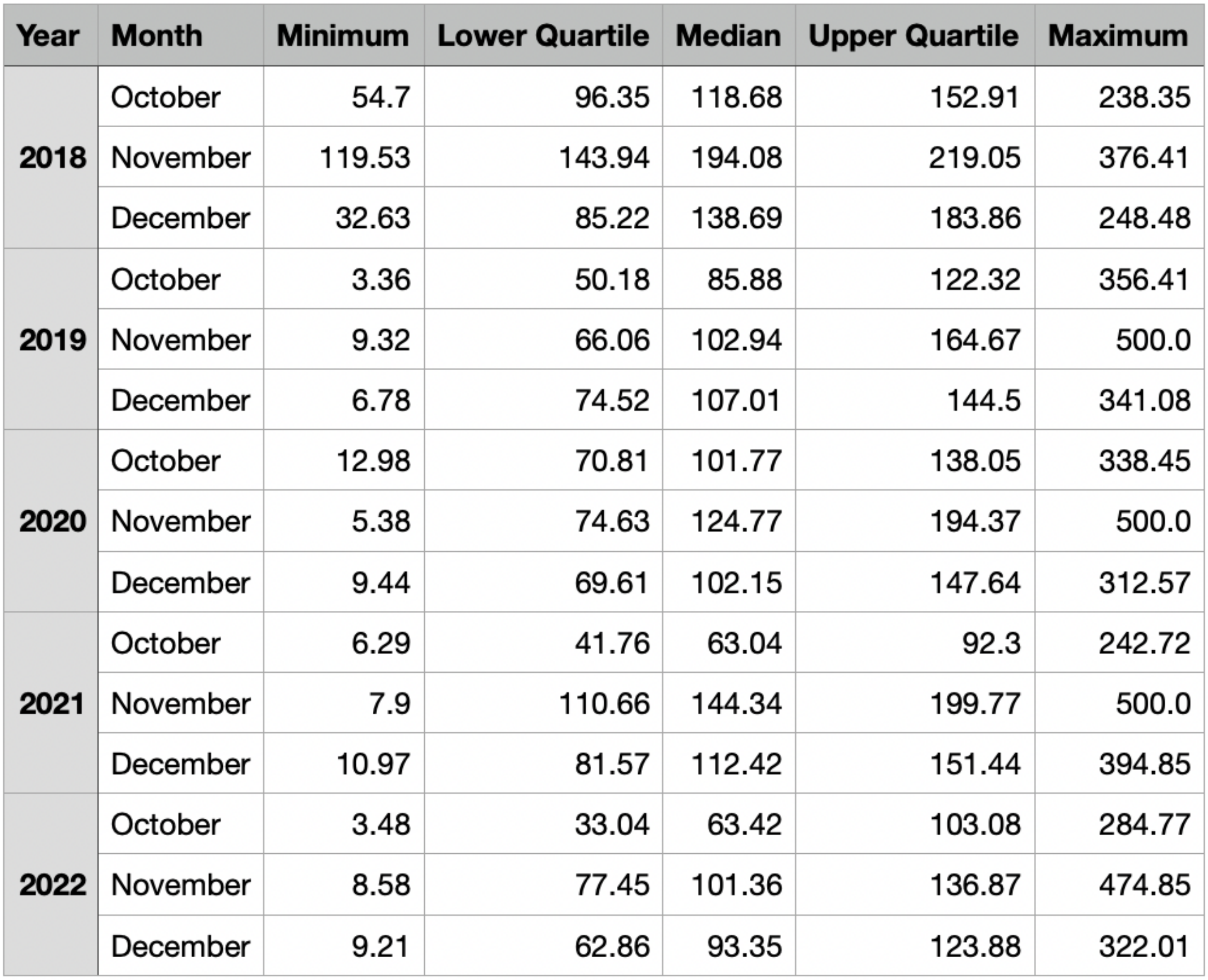
Fig 16: Distribution of PM2.5 from 2018-2023 in Punjab

The plot shows an increase in the PM2.5 concentration during both the crop burning seasons. While the deterioration in air quality cannot solely be attributed to stubble burning, it is important to acknowledge the role of other sources of air pollution. These sources include heightened vehicular traffic and various meteorological factors. Factors like the presence of La Nina and the formation of anticyclonic conditions in eastern regions of the country, coupled with weather patterns affecting wind direction and the the development of fog and mist over Northern India, significantly contribute to the complexity of air pollution in different geographical areas.

To get a deeper understanding of air quality in these states, we looked at the statistical distribution of PM2.5 concentration represented in Tables 2 to 9. We examined the months from October-December during kharif crop burning and from April to June during rabi crop burning. This helped us identify the months with unhealthy and hazardous air conditions from 2018-2023.

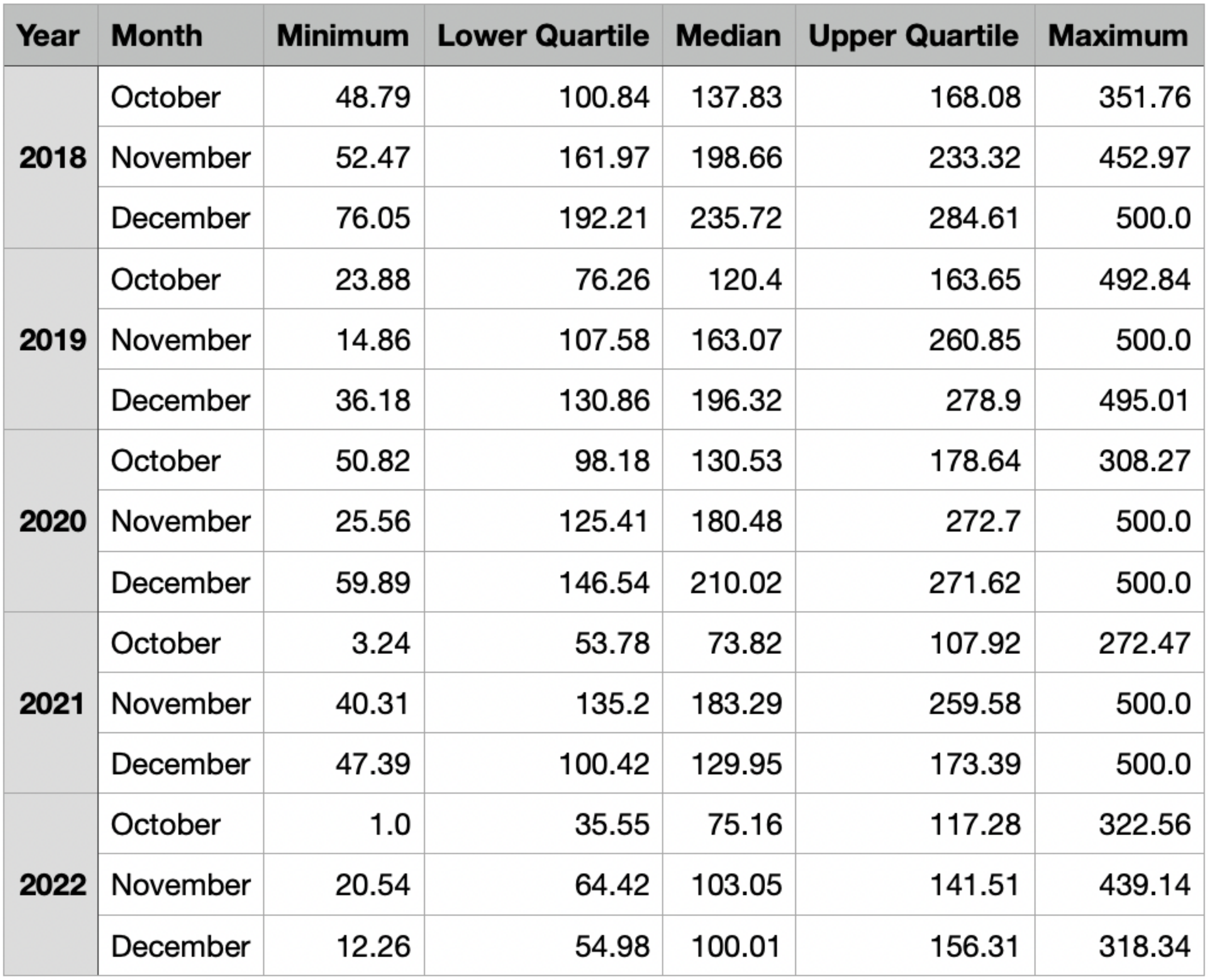
Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	October	19.9	41.26	48.87	63.52	235.65
	November	9.18	43.84	57.47	71.81	159.26
	December	13.51	41.9	56.93	70.17	107.42
2019	October	9.7	37.07	54.16	81.1	226.13
	November	13.35	45.41	82.85	113.42	247.76
	December	20.71	50.6	67.84	90.59	225.06
2020	October	13.14	53.01	67.9	80.0	183.82
	November	11.35	57.35	92.06	119.62	210.52
	December	13.56	44.92	64.98	82.17	159.23
2021	October	2.12	30.42	49.33	69.07	126.52
	November	0.24	78.0	93.32	110.0	201.92
	December	24.06	65.4	81.3	95.62	187.63
2022	October	11.65	39.02	55.98	75.48	171.87
	November	20.27	59.36	72.9	89.88	295.9
	December	2.27	56.56	74.6	93.65	172.07

Table 4: Distribution of PM2.5 concentration from October - December in Punjab



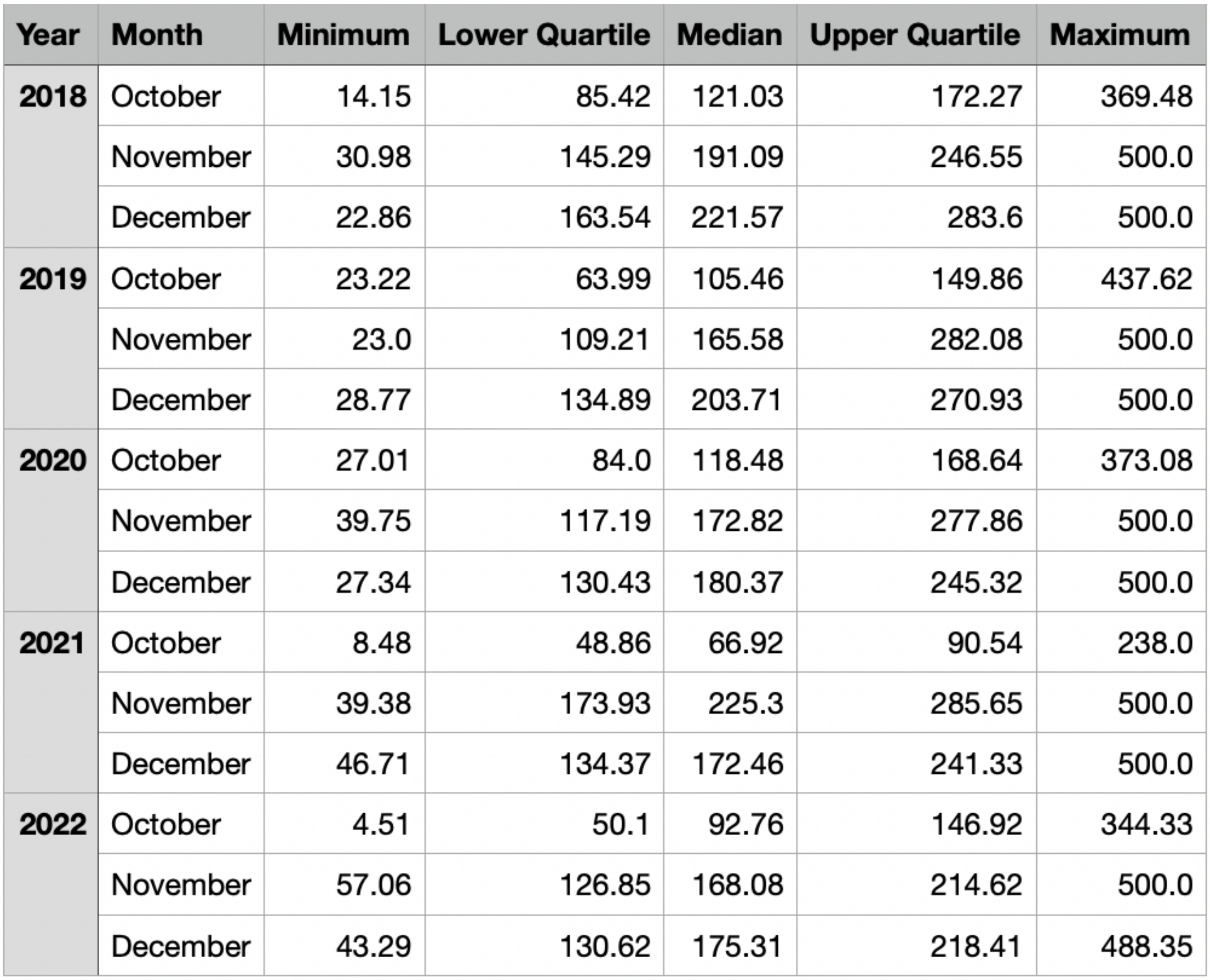
Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	October	54.7	96.35	118.68	152.91	238.35
	November	119.53	143.94	194.08	219.05	376.41
	December	32.63	85.22	138.69	183.86	248.48
2019	October	3.36	50.18	85.88	122.32	356.41
	November	9.32	66.06	102.94	164.67	500.0
	December	6.78	74.52	107.01	144.5	341.08
2020	October	12.98	70.81	101.77	138.05	338.45
	November	5.38	74.63	124.77	194.37	500.0
	December	9.44	69.61	102.15	147.64	312.57
2021	October	6.29	41.76	63.04	92.3	242.72
	November	7.9	110.66	144.34	199.77	500.0
	December	10.97	81.57	112.42	151.44	394.85
2022	October	3.48	33.04	63.42	103.08	284.77
	November	8.58	77.45	101.36	136.87	474.85
	December	9.21	62.86	93.35	123.88	322.01

Table 5: Distribution of PM2.5 concentration from October - December in Haryana



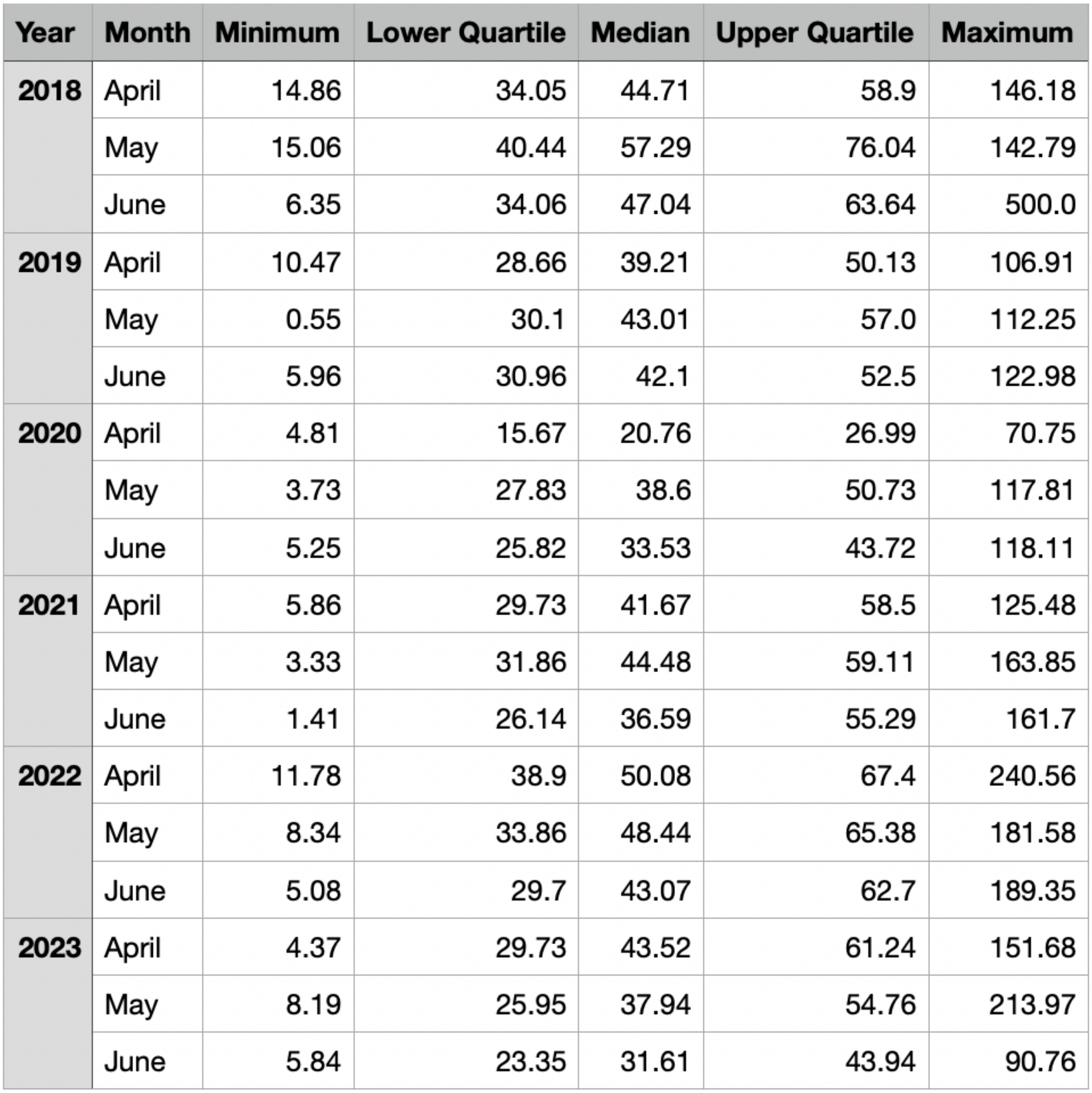
Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	October	48.79	100.84	137.83	168.08	351.76
	November	52.47	161.97	198.66	233.32	452.97
	December	76.05	192.21	235.72	284.61	500.0
2019	October	23.88	76.26	120.4	163.65	492.84
	November	14.86	107.58	163.07	260.85	500.0
	December	36.18	130.86	196.32	278.9	495.01
2020	October	50.82	98.18	130.53	178.64	308.27
	November	25.56	125.41	180.48	272.7	500.0
	December	59.89	146.54	210.02	271.62	500.0
2021	October	3.24	53.78	73.82	107.92	272.47
	November	40.31	135.2	183.29	259.58	500.0
	December	47.39	100.42	129.95	173.39	500.0
2022	October	1.0	35.55	75.16	117.28	322.56
	November	20.54	64.42	103.05	141.51	439.14
	December	12.26	54.98	100.01	156.31	318.34

Table 6: Distribution of PM2.5 concentration from October - December in Uttar Pradesh



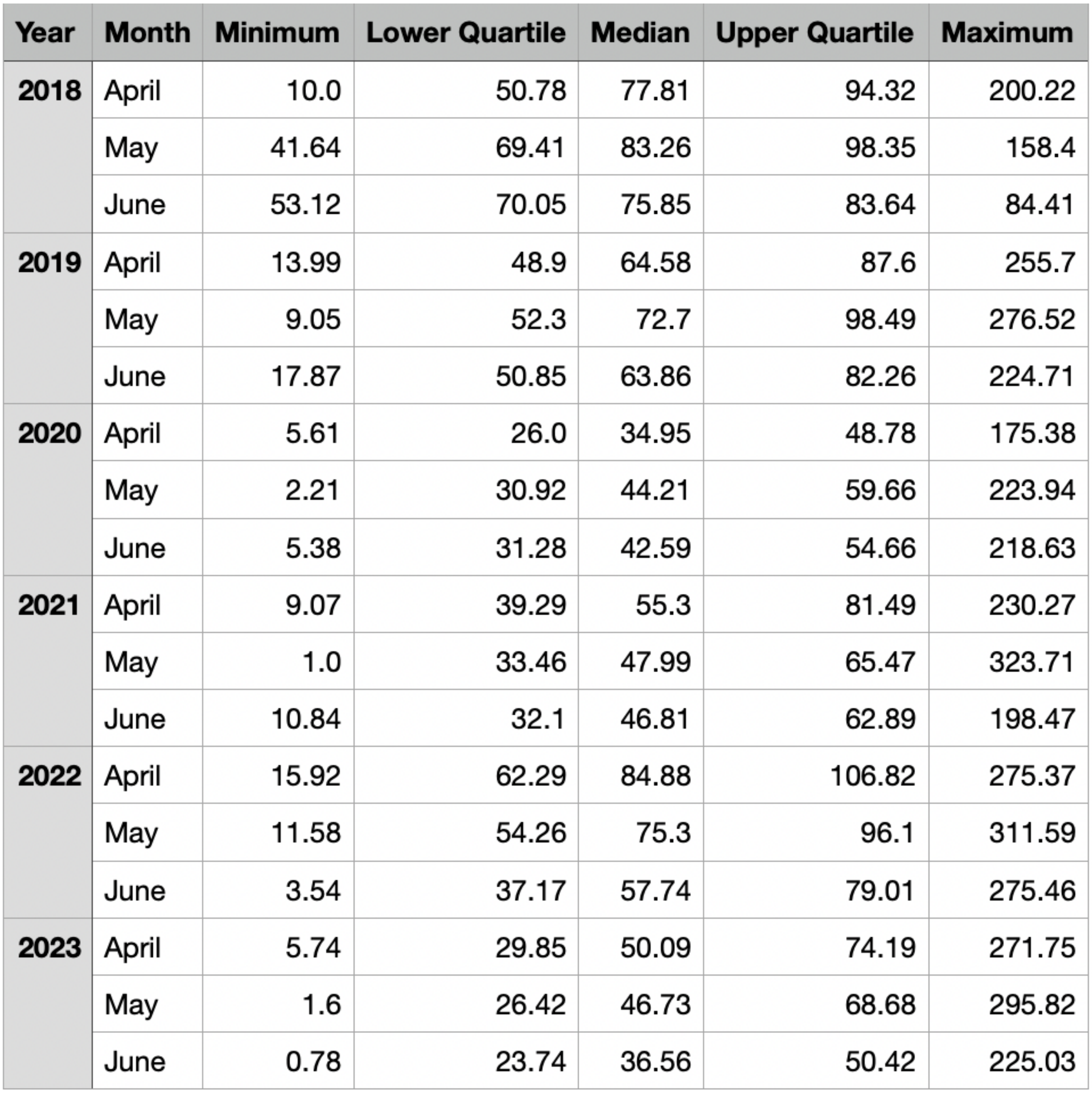
Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	October	14.15	85.42	121.03	172.27	369.48
	November	30.98	145.29	191.09	246.55	500.0
	December	22.86	163.54	221.57	283.6	500.0
2019	October	23.22	63.99	105.46	149.86	437.62
	November	23.0	109.21	165.58	282.08	500.0
	December	28.77	134.89	203.71	270.93	500.0
2020	October	27.01	84.0	118.48	168.64	373.08
	November	39.75	117.19	172.82	277.86	500.0
	December	27.34	130.43	180.37	245.32	500.0
2021	October	8.48	48.86	66.92	90.54	238.0
	November	39.38	173.93	225.3	285.65	500.0
	December	46.71	134.37	172.46	241.33	500.0
2022	October	4.51	50.1	92.76	146.92	344.33
	November	57.06	126.85	168.08	214.62	500.0
	December	43.29	130.62	175.31	218.41	488.35

Table 7: Distribution of PM2.5 concentration from October - December in Delhi



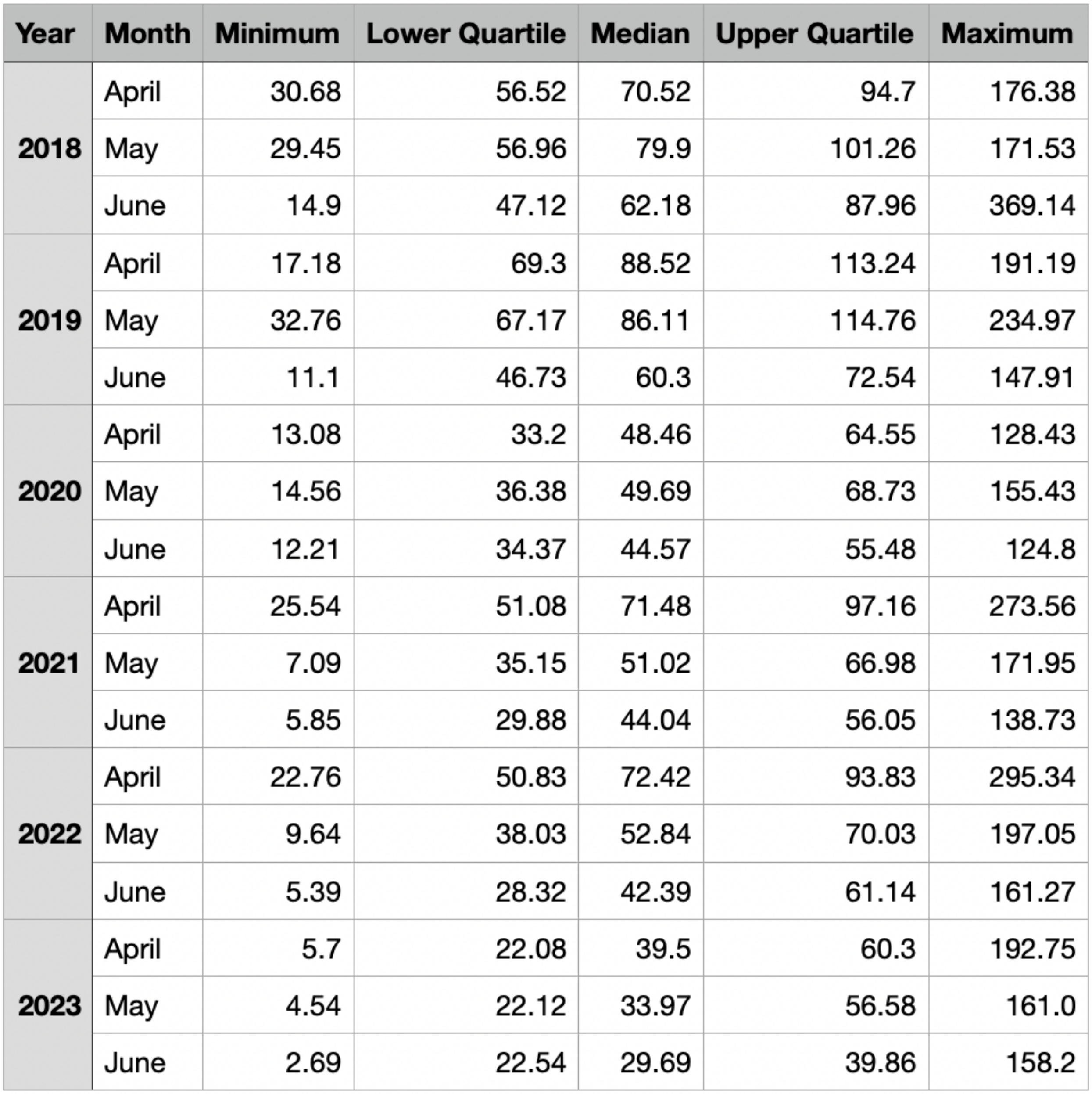
Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	April	14.86	34.05	44.71	58.9	146.18
	May	15.06	40.44	57.29	76.04	142.79
	June	6.35	34.06	47.04	63.64	500.0
2019	April	10.47	28.66	39.21	50.13	106.91
	May	0.55	30.1	43.01	57.0	112.25
	June	5.96	30.96	42.1	52.5	122.98
2020	April	4.81	15.67	20.76	26.99	70.75
	May	3.73	27.83	38.6	50.73	117.81
	June	5.25	25.82	33.53	43.72	118.11
2021	April	5.86	29.73	41.67	58.5	125.48
	May	3.33	31.86	44.48	59.11	163.85
	June	1.41	26.14	36.59	55.29	161.7
2022	April	11.78	38.9	50.08	67.4	240.56
	May	8.34	33.86	48.44	65.38	181.58
	June	5.08	29.7	43.07	62.7	189.35
2023	April	4.37	29.73	43.52	61.24	151.68
	May	8.19	25.95	37.94	54.76	213.97
	June	5.84	23.35	31.61	43.94	90.76

Table 8: Distribution of PM2.5 concentration from April - June in Punjab



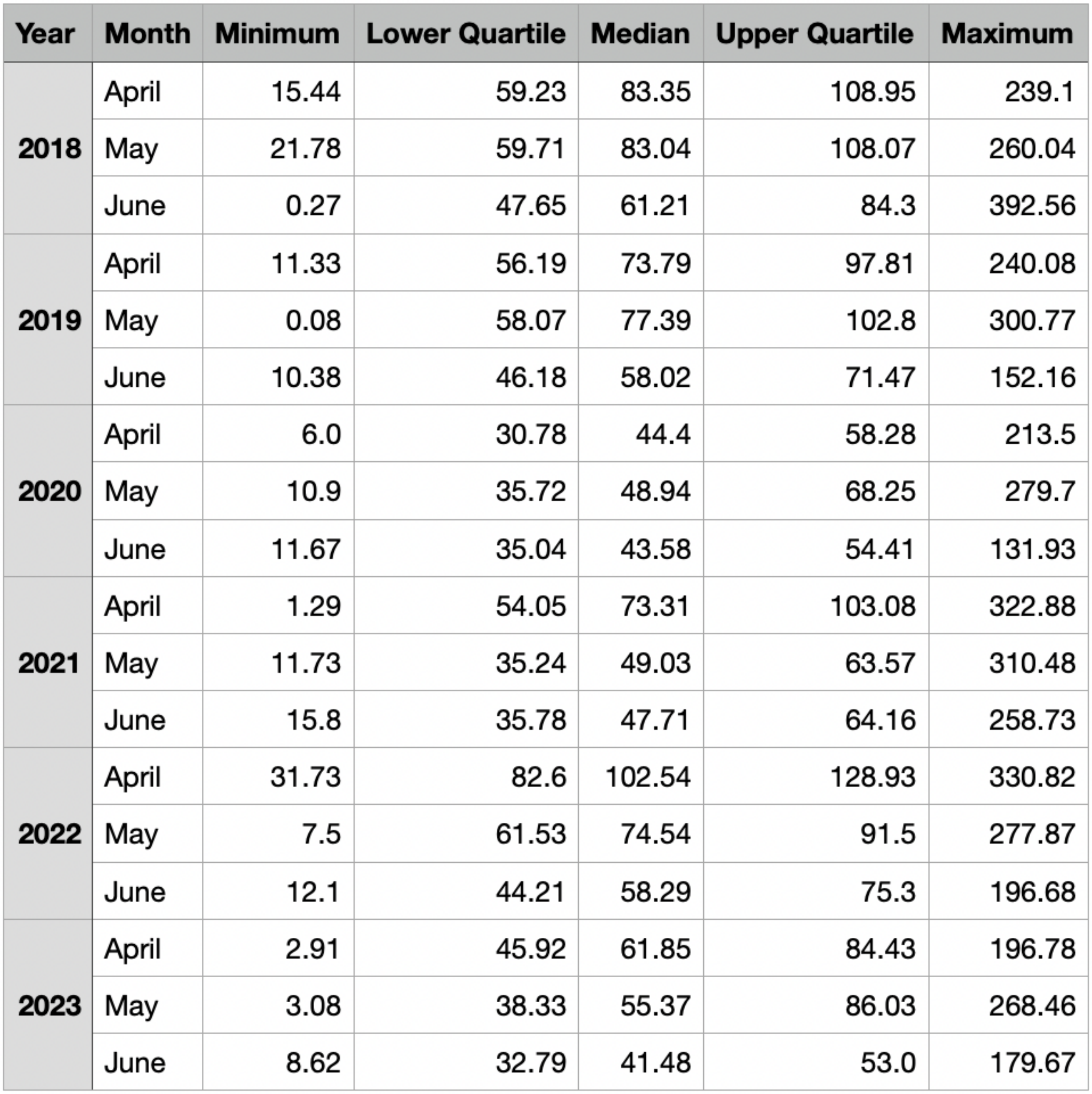
Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	April	10.0	50.78	77.81	94.32	200.22
	May	41.64	69.41	83.26	98.35	158.4
	June	53.12	70.05	75.85	83.64	84.41
2019	April	13.99	48.9	64.58	87.6	255.7
	May	9.05	52.3	72.7	98.49	276.52
	June	17.87	50.85	63.86	82.26	224.71
2020	April	5.61	26.0	34.95	48.78	175.38
	May	2.21	30.92	44.21	59.66	223.94
	June	5.38	31.28	42.59	54.66	218.63
2021	April	9.07	39.29	55.3	81.49	230.27
	May	1.0	33.46	47.99	65.47	323.71
	June	10.84	32.1	46.81	62.89	198.47
2022	April	15.92	62.29	84.88	106.82	275.37
	May	11.58	54.26	75.3	96.1	311.59
	June	3.54	37.17	57.74	79.01	275.46
2023	April	5.74	29.85	50.09	74.19	271.75
	May	1.6	26.42	46.73	68.68	295.82
	June	0.78	23.74	36.56	50.42	225.03

Table 9: Distribution of PM2.5 concentration from April - June in Haryana



Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	April	30.68	56.52	70.52	94.7	176.38
	May	29.45	56.96	79.9	101.26	171.53
	June	14.9	47.12	62.18	87.96	369.14
2019	April	17.18	69.3	88.52	113.24	191.19
	May	32.76	67.17	86.11	114.76	234.97
	June	11.1	46.73	60.3	72.54	147.91
2020	April	13.08	33.2	48.46	64.55	128.43
	May	14.56	36.38	49.69	68.73	155.43
	June	12.21	34.37	44.57	55.48	124.8
2021	April	25.54	51.08	71.48	97.16	273.56
	May	7.09	35.15	51.02	66.98	171.95
	June	5.85	29.88	44.04	56.05	138.73
2022	April	22.76	50.83	72.42	93.83	295.34
	May	9.64	38.03	52.84	70.03	197.05
	June	5.39	28.32	42.39	61.14	161.27
2023	April	5.7	22.08	39.5	60.3	192.75
	May	4.54	22.12	33.97	56.58	161.0
	June	2.69	22.54	29.69	39.86	158.2

Table 10: Distribution of PM2.5 concentration April - June in Uttar Pradesh



Year	Month	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
2018	April	15.44	59.23	83.35	108.95	239.1
	May	21.78	59.71	83.04	108.07	260.04
	June	0.27	47.65	61.21	84.3	392.56
2019	April	11.33	56.19	73.79	97.81	240.08
	May	0.08	58.07	77.39	102.8	300.77
	June	10.38	46.18	58.02	71.47	152.16
2020	April	6.0	30.78	44.4	58.28	213.5
	May	10.9	35.72	48.94	68.25	279.7
	June	11.67	35.04	43.58	54.41	131.93
2021	April	1.29	54.05	73.31	103.08	322.88
	May	11.73	35.24	49.03	63.57	310.48
	June	15.8	35.78	47.71	64.16	258.73
2022	April	31.73	82.6	102.54	128.93	330.82
	May	7.5	61.53	74.54	91.5	277.87
	June	12.1	44.21	58.29	75.3	196.68
2023	April	2.91	45.92	61.85	84.43	196.78
	May	3.08	38.33	55.37	86.03	268.46
	June	8.62	32.79	41.48	53.0	179.67

Table 11: Distribution of PM2.5 concentration from April - June in Delhi

Further we wanted to understand the dynamics of PM2.5 across these states at a granular level, for which we plotted the daily maximum PM2.5 for the two seasons in consideration those are 15 September to 31 December (burning of kharif) and 15 March to 30 June (burning of rabi). The plot also emphasizes on the different categories of Air Quality Index by the respective color.

The AQI values and corresponding ambient concentrations (health breakpoints) as well as associated likely impacts for the identified pollutants are as follows:

AQI Category	**PM2.5 (24 hr)**	**PM10 (24 hr)**	**Possible Health Impacts**
Good (0-50)	0-30	0-50	Minimal impact
Satisfactory (51-100)	31-60	51-100	Minor breathing discomfort to sensitive people
Moderately Polluted (101-200)	61-90	101-250	Breathing discomfort to the people with lungs, asthma and heart diseases
Poor (201-300)	91-120	250-350	Breathing discomfort to most people on prolonged exposure
Very Poor (301-400)	121-250	351-430	Respiratory illness on prolonged exposure
Severe (401-500)	250+	430+	Affects healthy people and seriously impacts those with existing diseases

(Source 1: https://pib.gov.in/newsite/printrelease.aspx?relid=110654 , Source 2: https://app.cpcbccr.com/AQI_India/)

Fig 17 to Fig 21 represents the daily maximum PM2.5 during the kharif crop burning season in Punjab from 2018 to 2022.

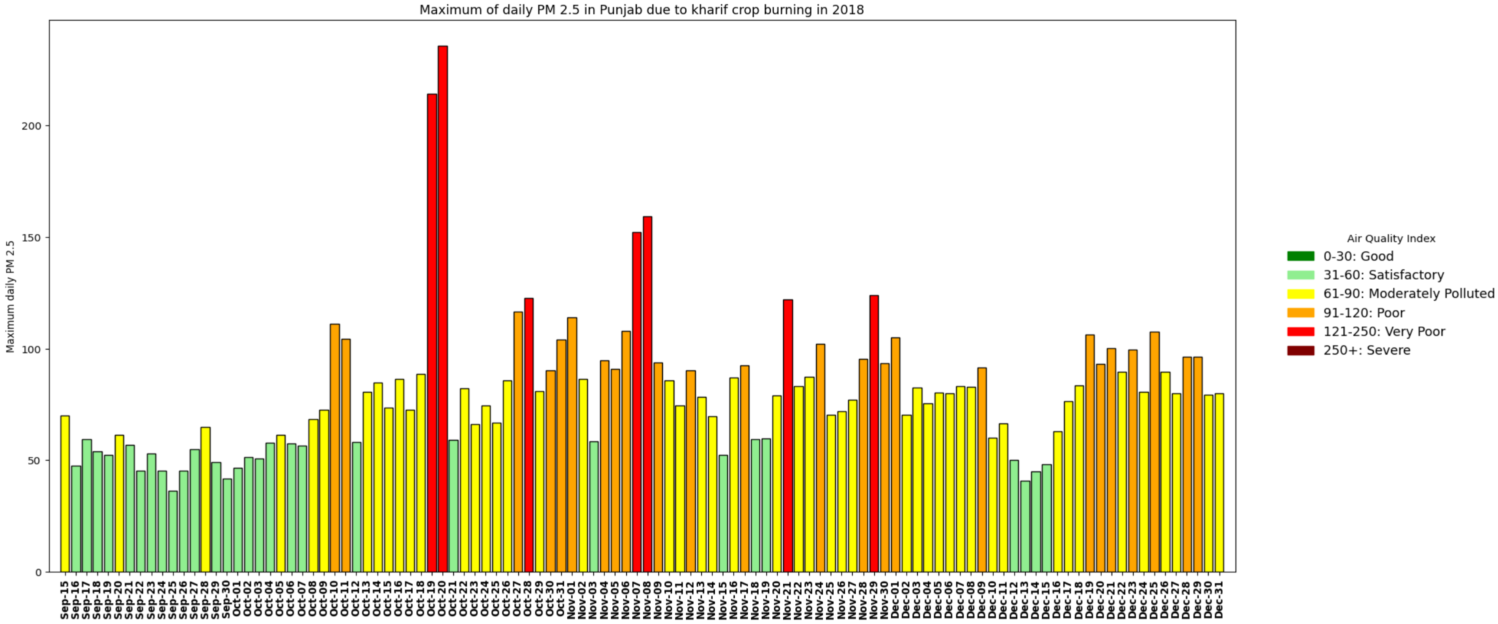


Fig 17: Daily maximum PM2.5 in Punjab from 15 September to 31 December in 2018

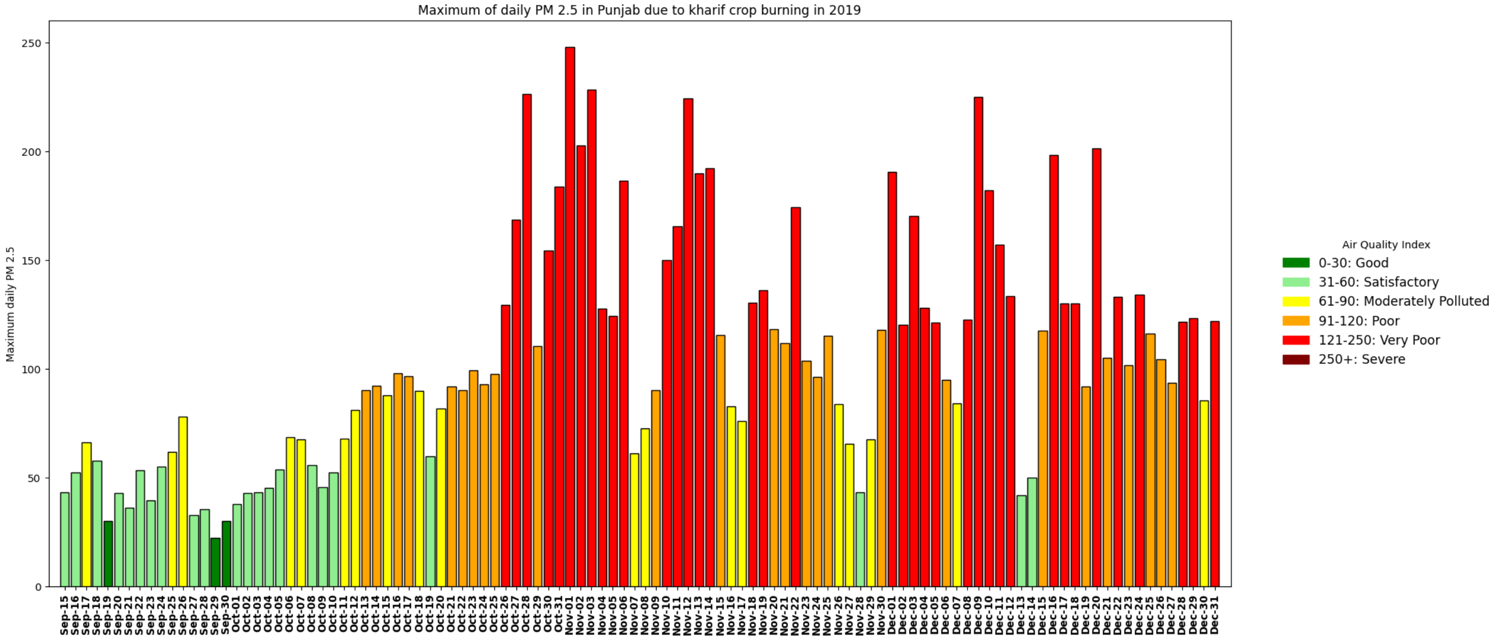


Fig 18: Daily maximum PM2.5 in Punjab from 15 September to 31 December in 2019

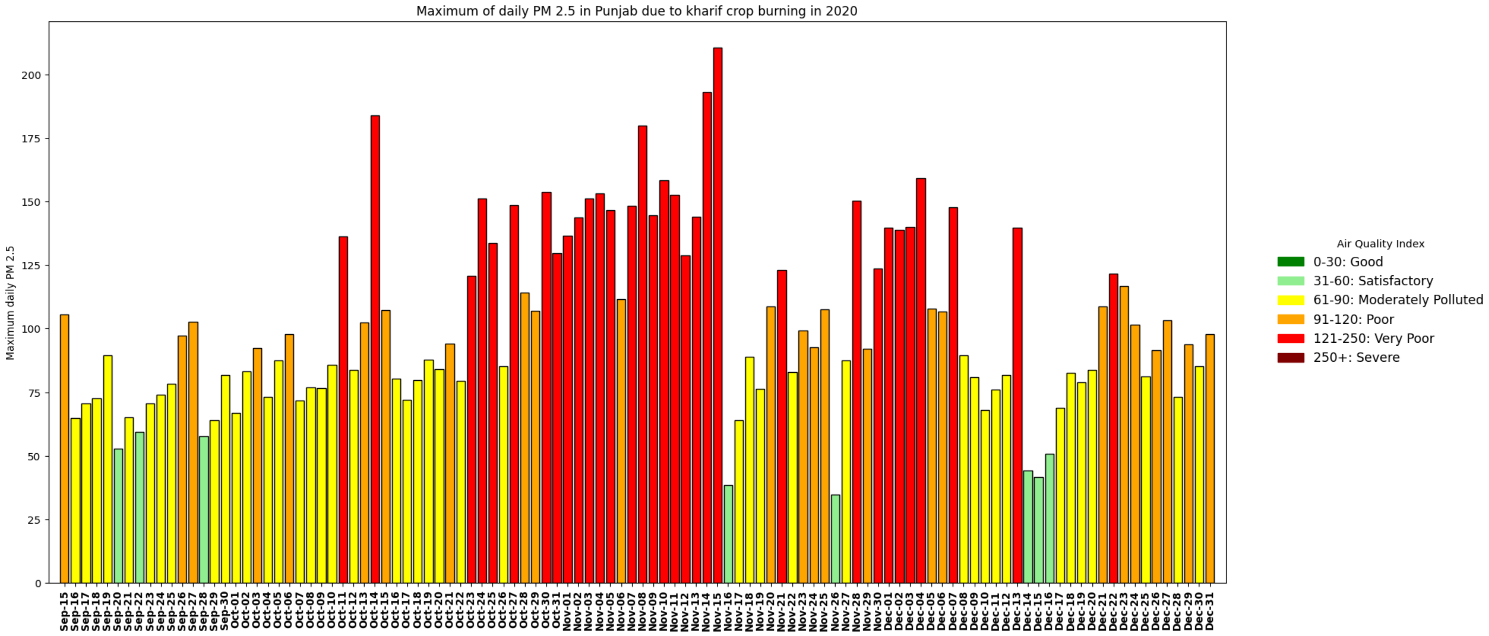


Fig 19: Daily maximum PM2.5 in Punjab from 15 September to 31 December in 2020

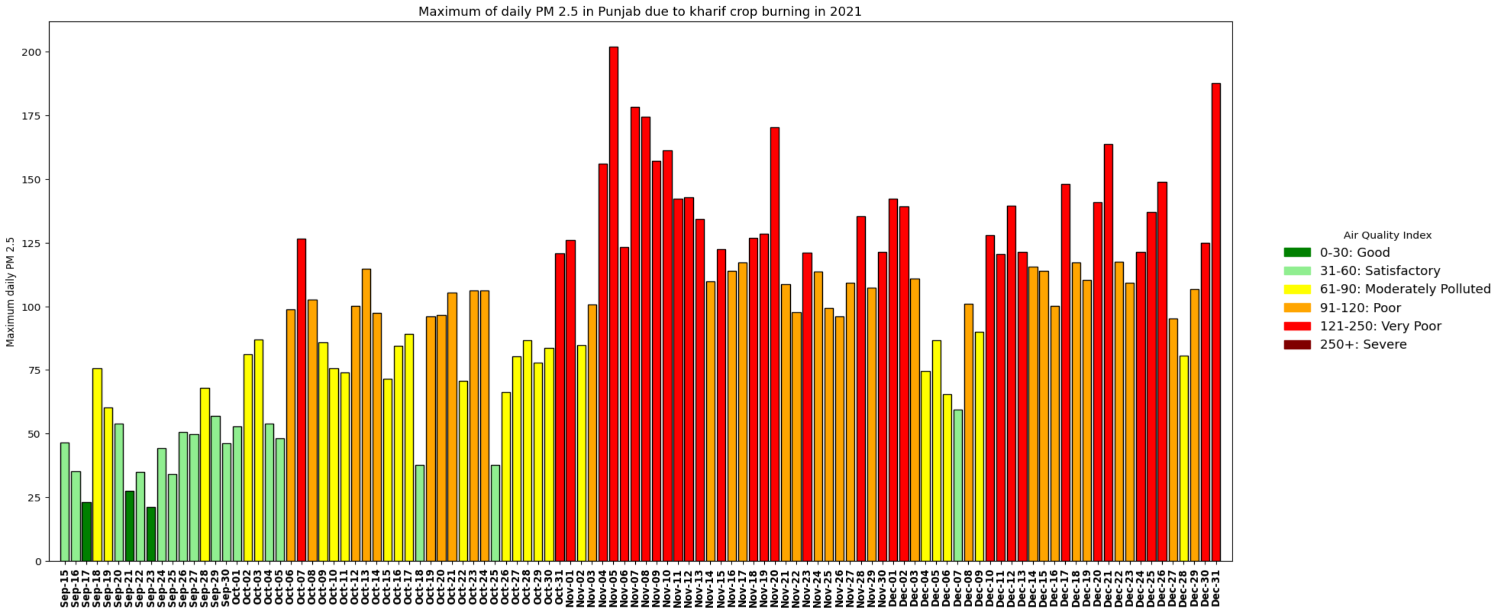


Fig 20: Daily maximum PM2.5 in Punjab from 15 September to 31 December in 2021

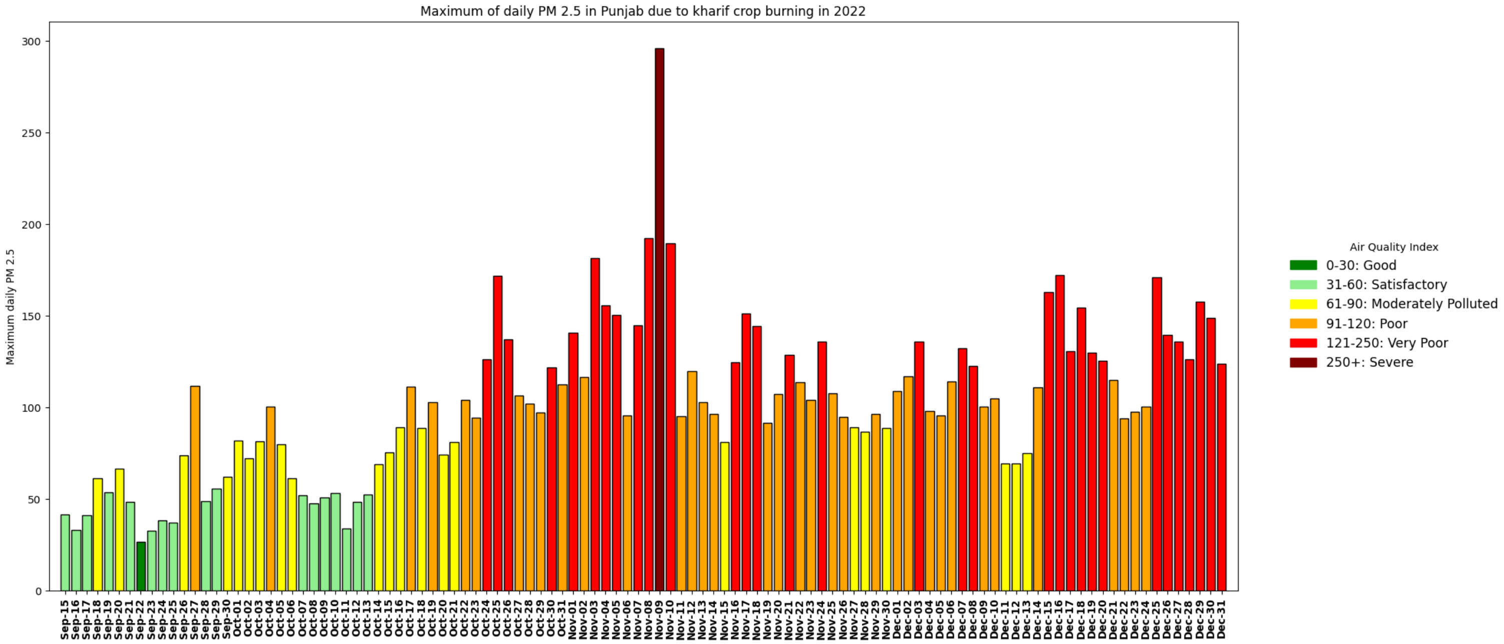


Fig 21: Daily maximum PM2.5 in Punjab from 15 September to 31 December in 2022

Fig 22 to Fig 27 represents the daily maximum PM2.5 during the kharif crop burning season in Haryana from 2018 to 2022.

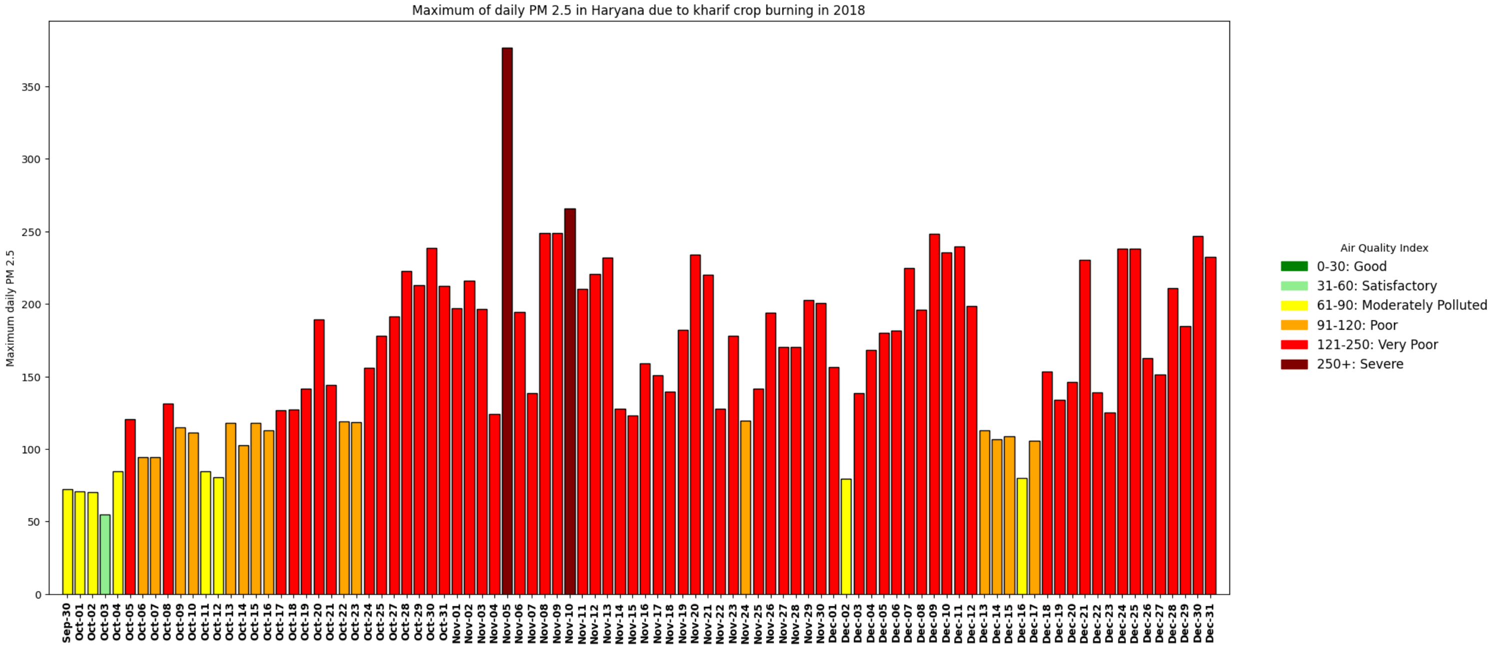


Fig 22: Daily maximum PM2.5 in Haryana from 15 September to 31 December in 2018

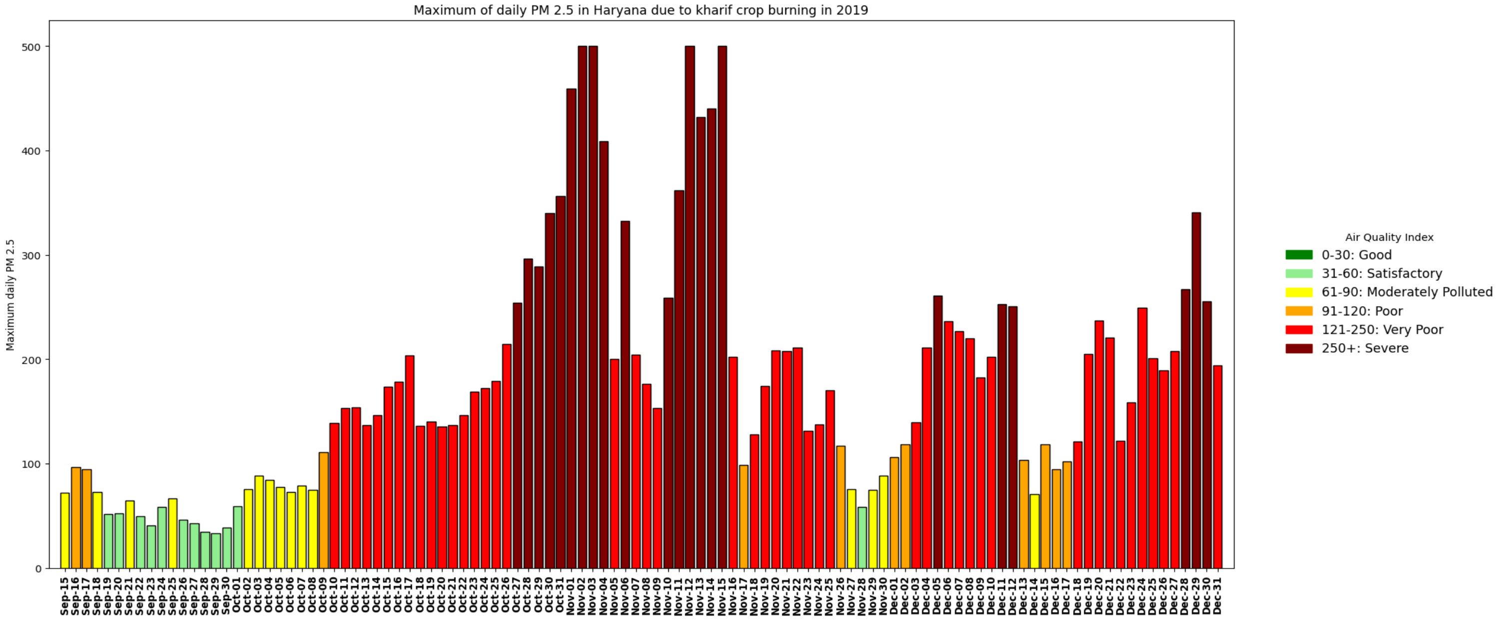


Fig 23: Daily maximum PM2.5 in Haryana from 15 September to 31 December in 2019

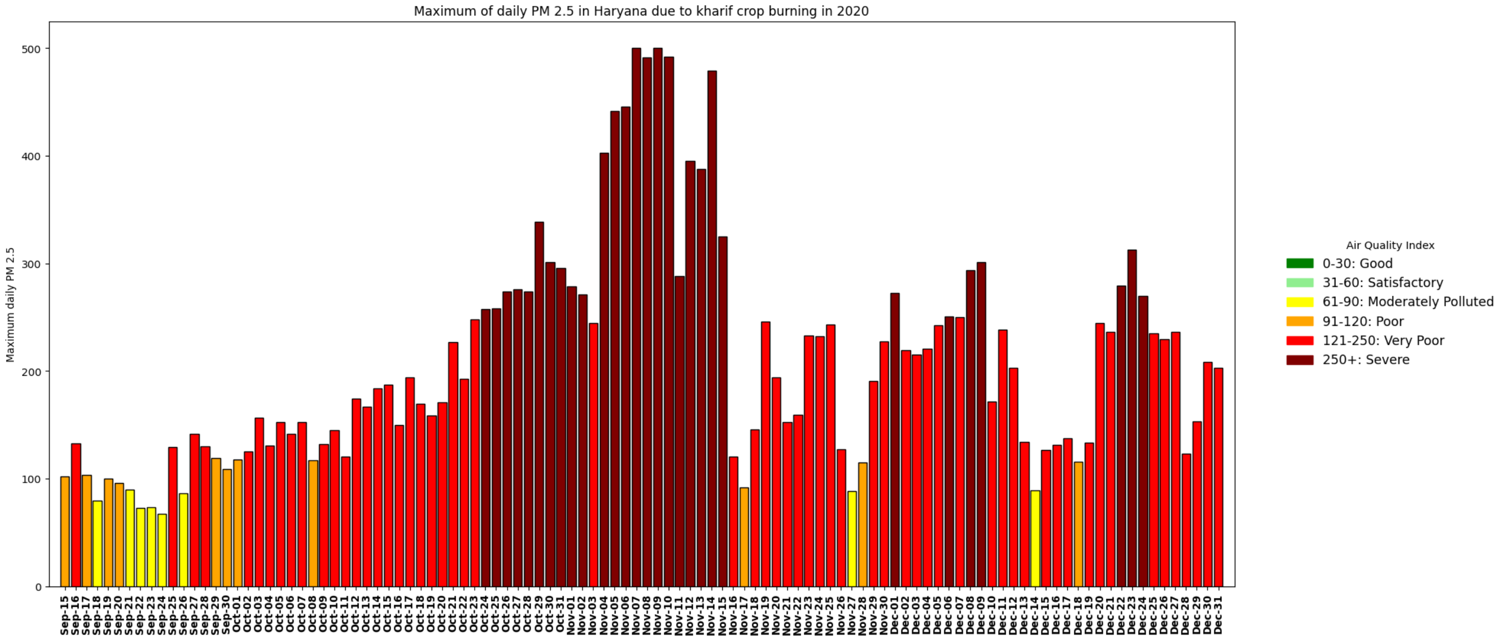


Fig 24: Daily maximum PM2.5 in Haryana from 15 September to 31 December in 2020

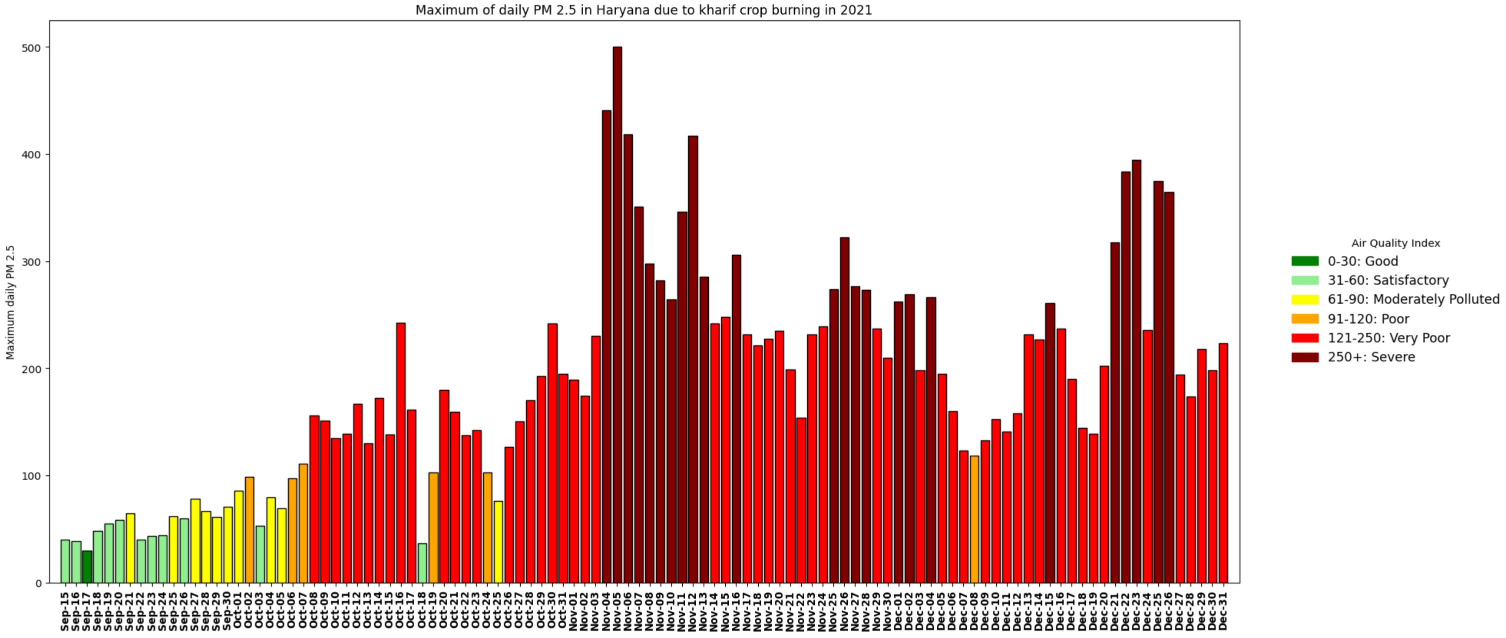


Fig 25: Daily maximum PM2.5 in Haryana from 15 September to 31 December in 2021

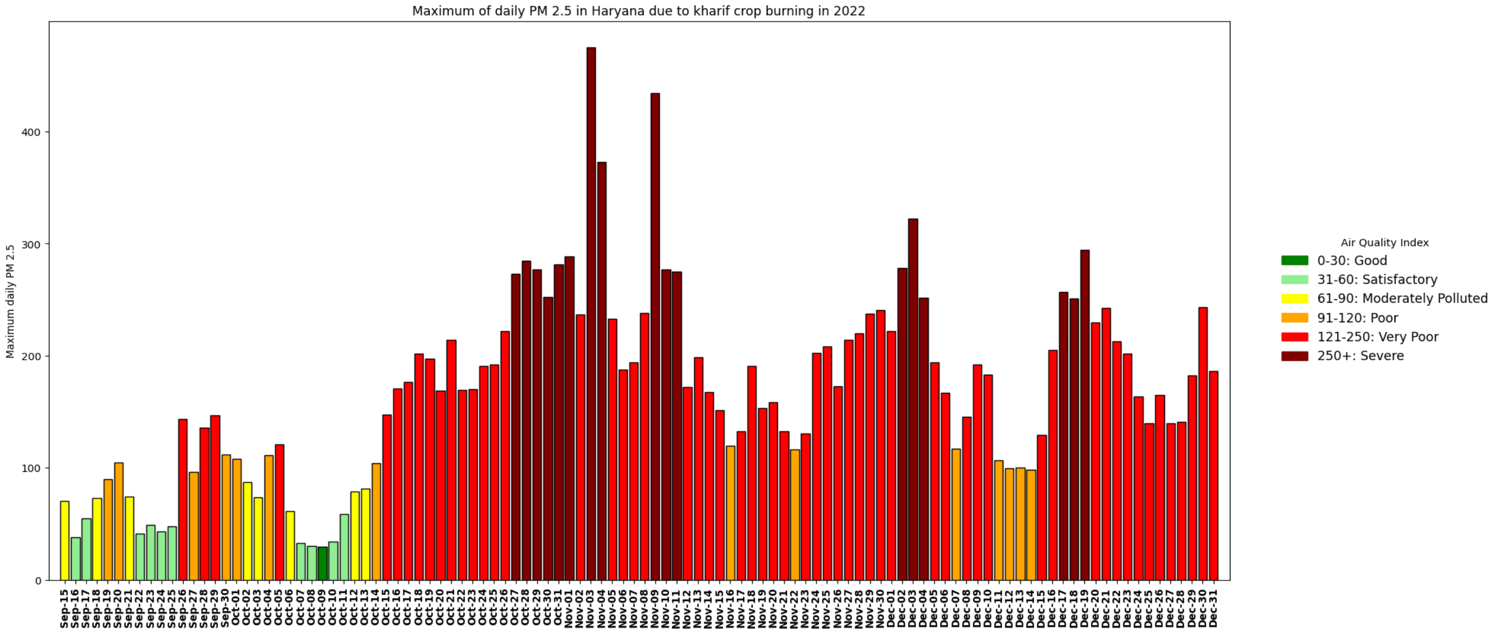


Fig 26: Daily maximum PM2.5 in Haryana from 15 September to 31 December in 2022

Fig 27 to Fig 31 represents daily maximum PM2.5 during the kharif crop burning season in Uttar Pradesh from 2018 to 2022.

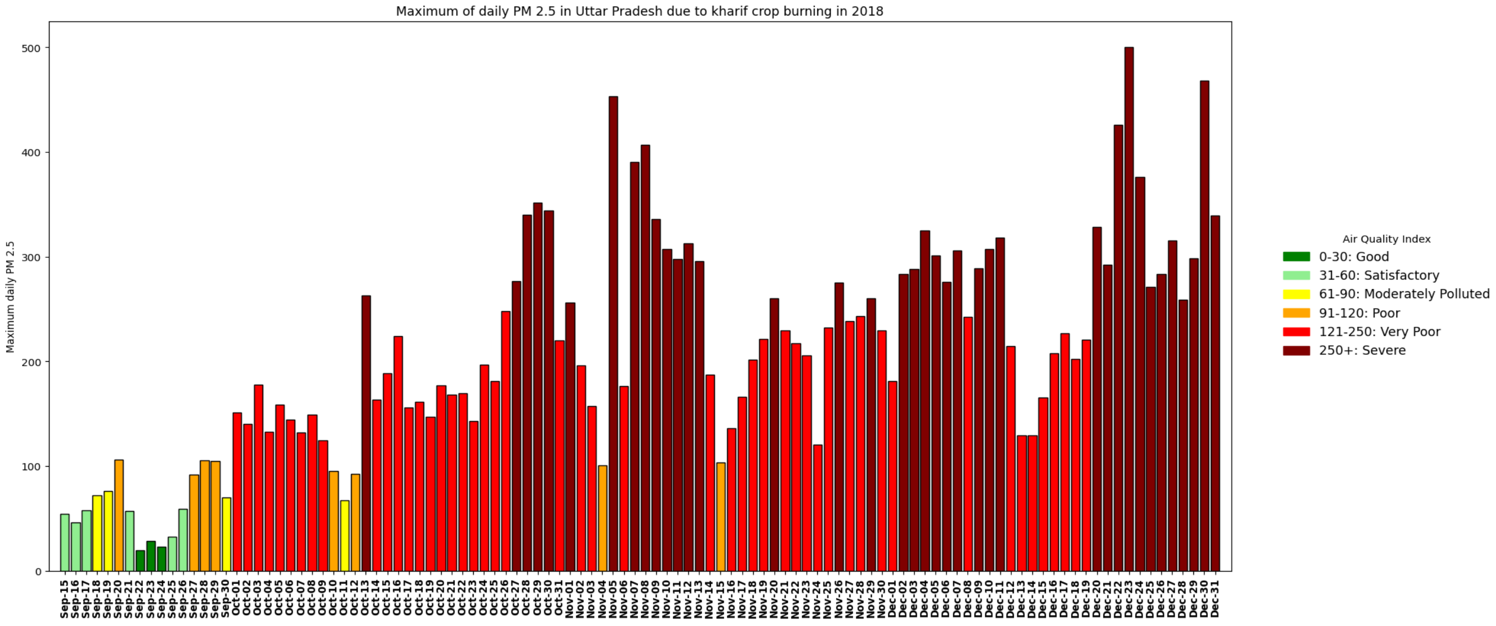


Fig 27: Daily maximum PM2.5 in Uttar Pradesh from 15 September to 31 December in 2018

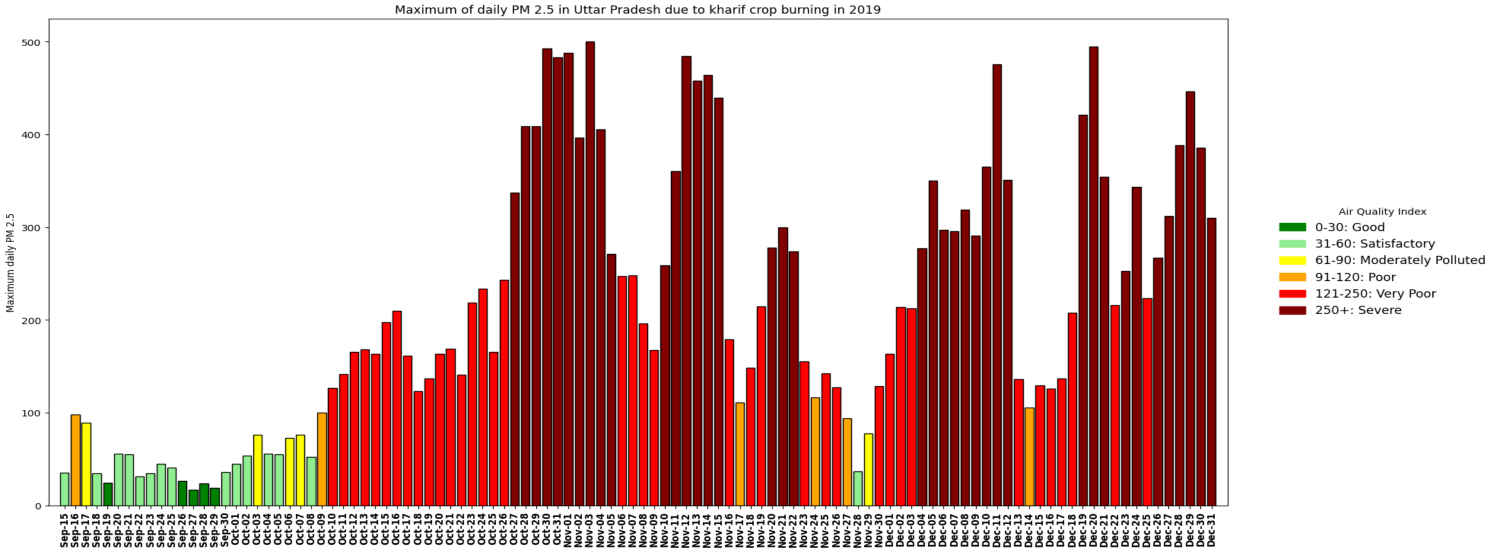


Fig 28: Daily maximum PM2.5 in Uttar Pradesh from 15 September to 31 December in 2019

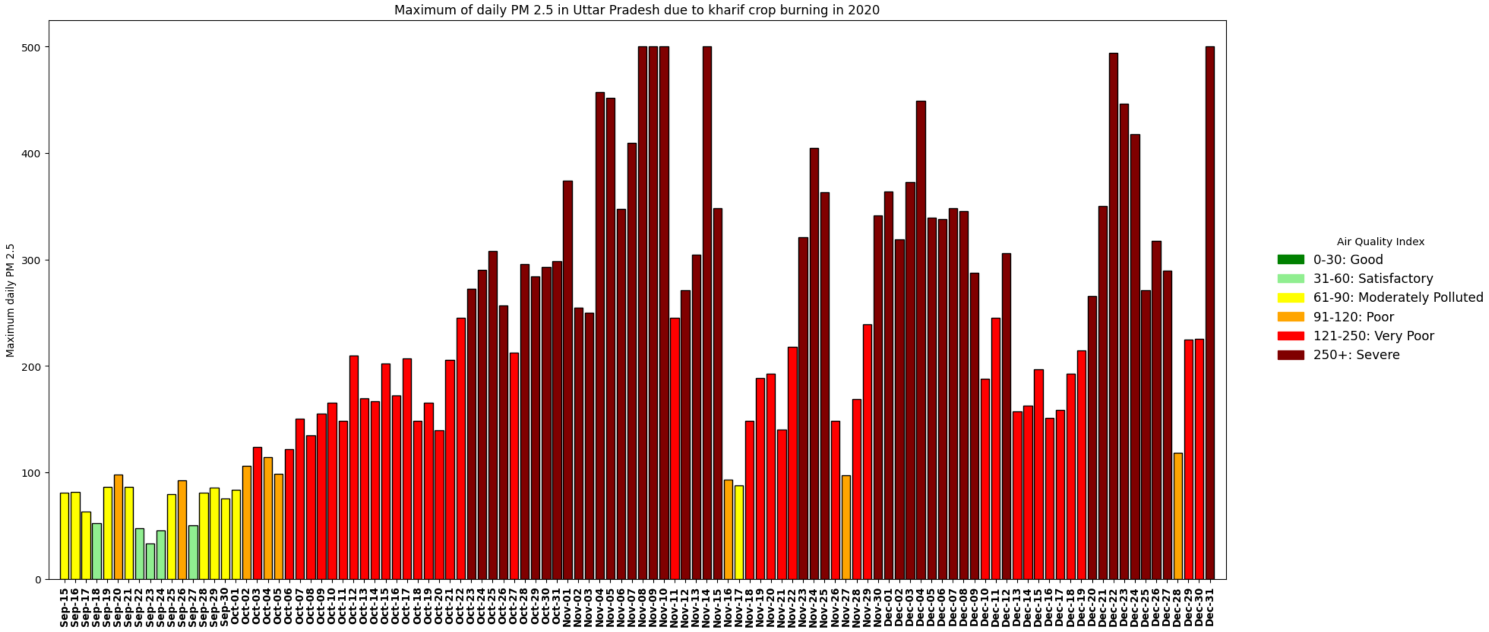


Fig 29: Daily maximum PM2.5 in Uttar Pradesh from 15 September to 31 December in 2020

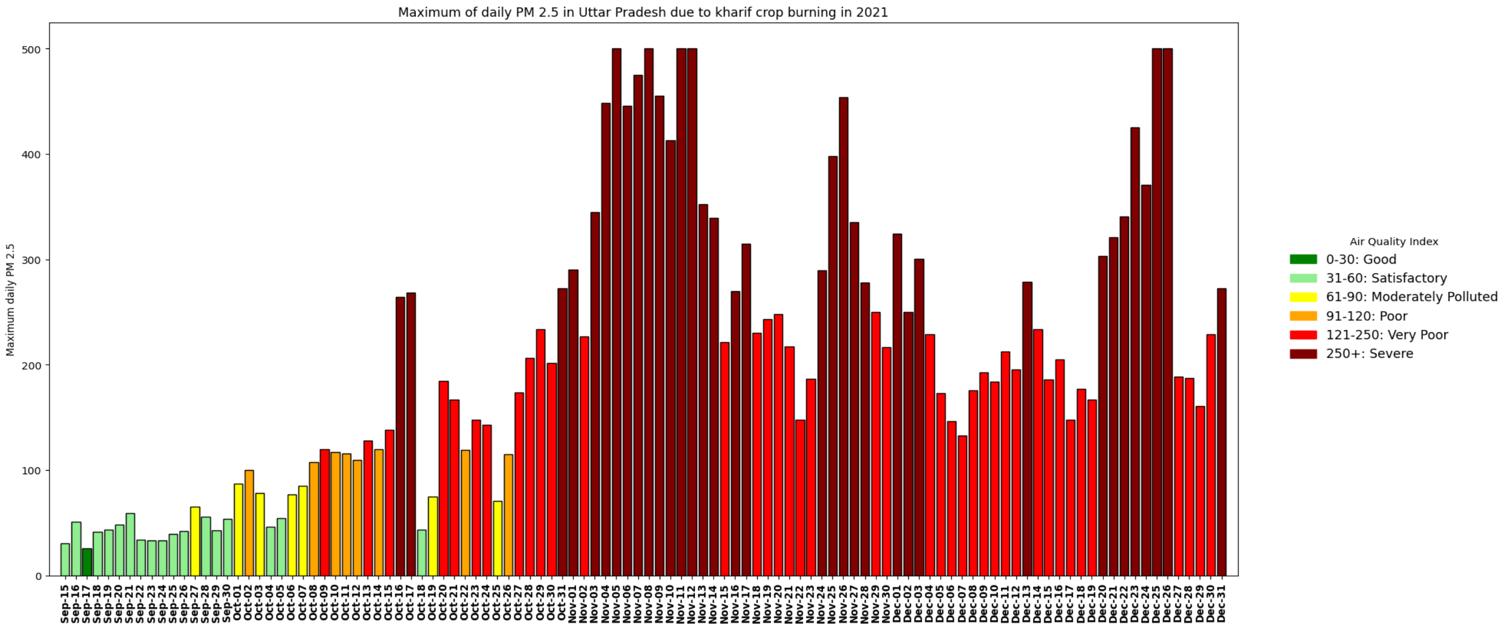


Fig 30: Daily maximum PM2.5 in Uttar Pradesh from 15 September to 31 December in 2021

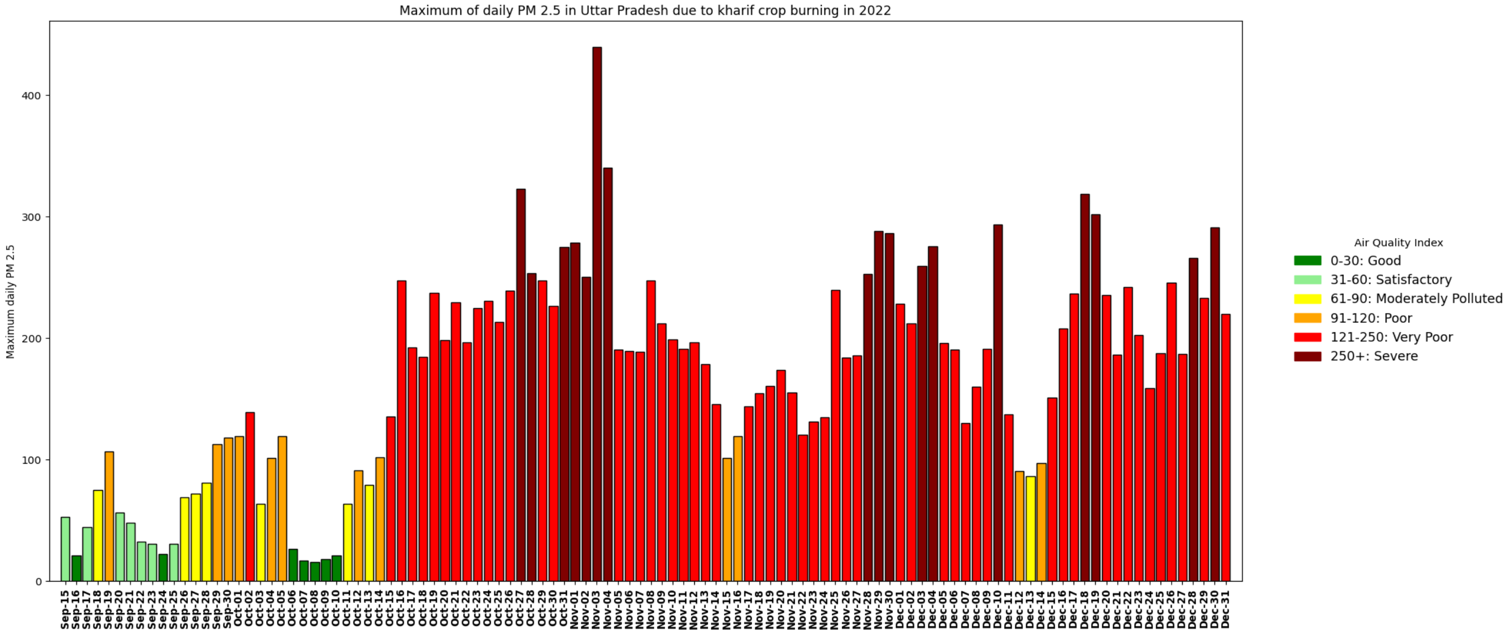


Fig 31: Daily maximum PM2.5 in Uttar Pradesh from 15 September to 31 December in 2022

Fig 32 to Fig 36 represents the daily maximum PM2.5 during the kharif crop burning season in Delhi from 2018 to 2022.

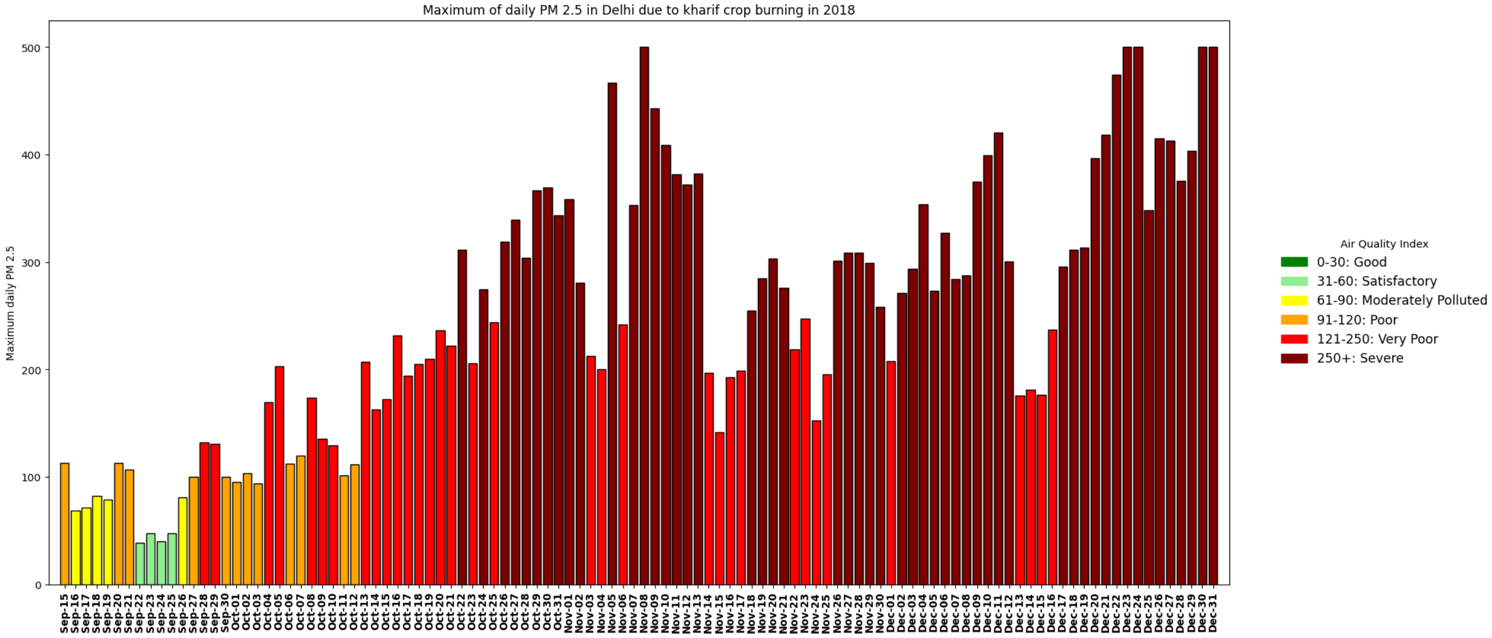


Fig 32: Daily maximum PM2.5 in Delhi from 15 September to 31 December in 2018

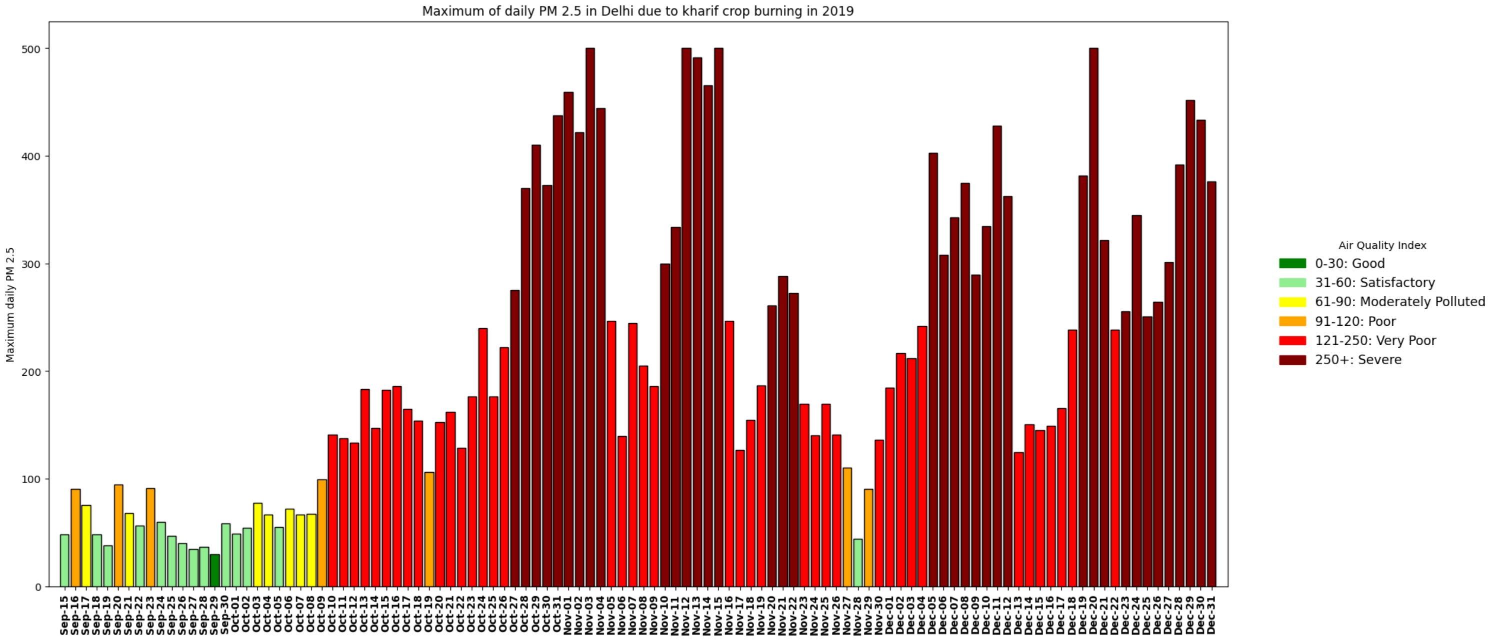


Fig 33: Daily maximum PM2.5 in Delhi from 15 September to 31 December in 2019

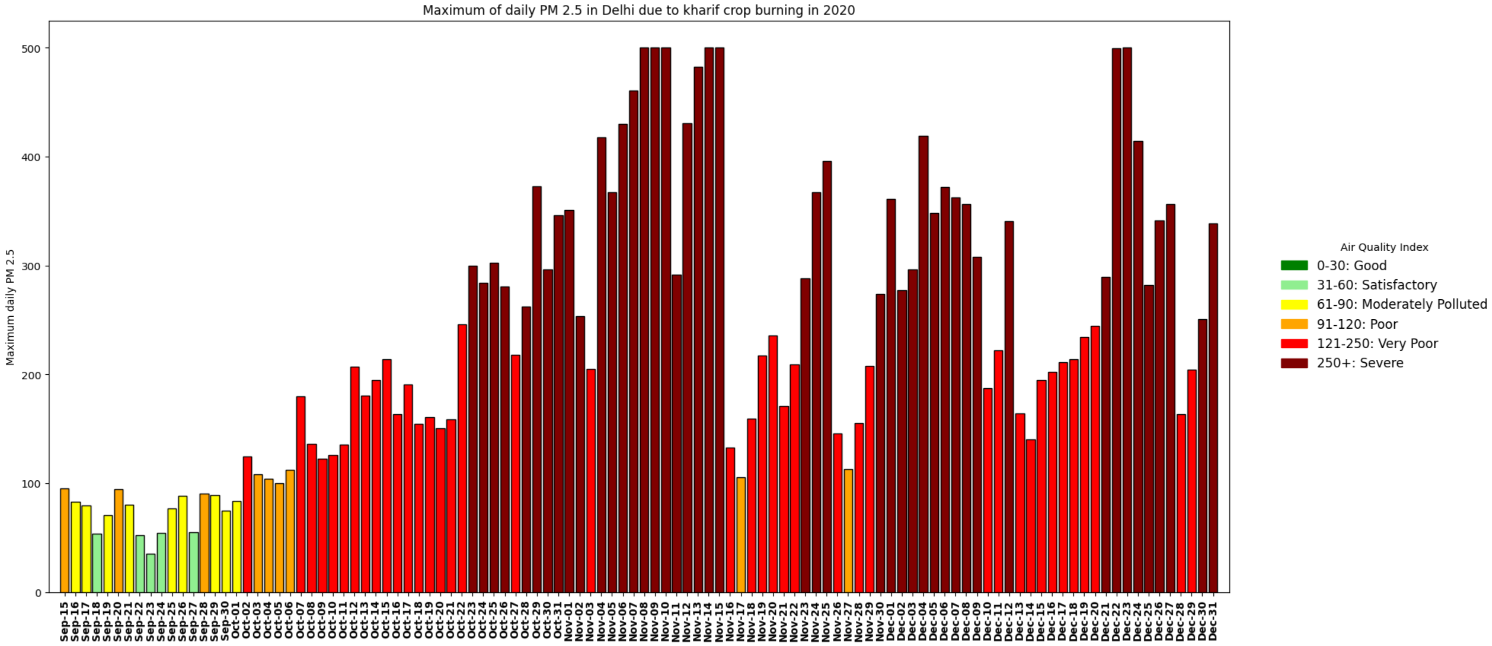


Fig 34: Daily maximum PM2.5 in Delhi from 15 September to 31 December in 2020

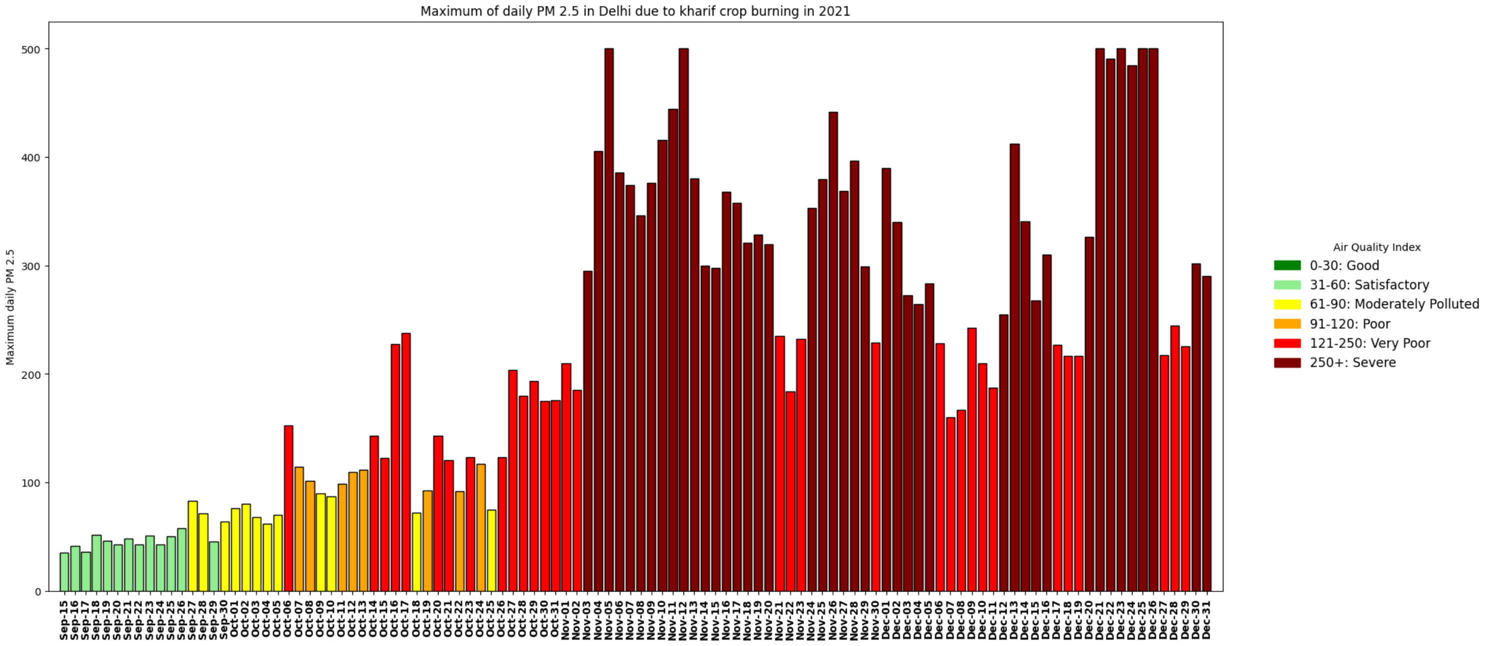


Fig 35: Daily maximum PM2.5 in Delhi from 15 September to 31 December in 2021

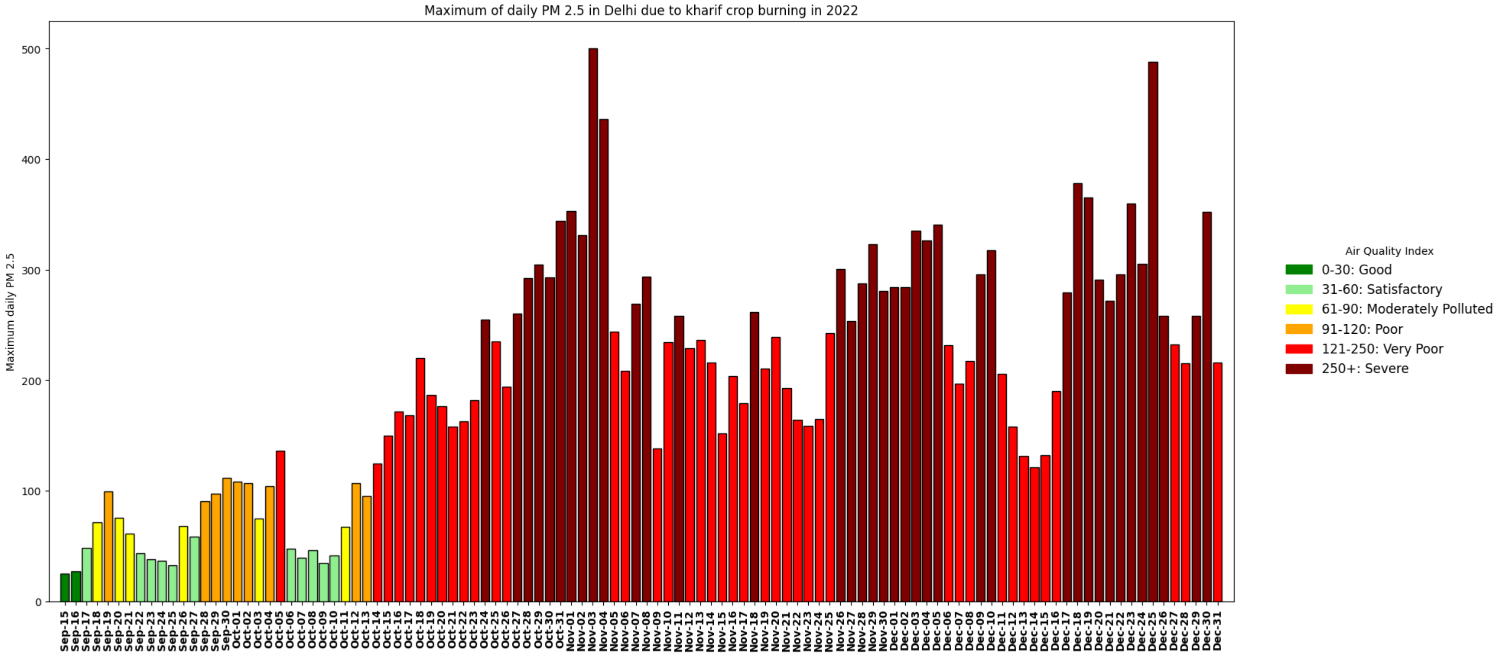


Fig 36: Daily maximum PM2.5 in Delhi from 15 September to 31 December in 2022

Summarising the findings from Figs 17 to Fig 36, our goal was to determine the percentage of days during which the maximum PM2.5 air quality levels fell into the categories of moderately polluted, poor, very poor and severe. We analyzed a total of 108 days, spanning from 15 September to 31 December (kharif crop burning), for each state and each year from 2018 to 2022.

Year	**Moderately polluted PM2.5 (61-90)**	**Poor PM2.5 (91-120)**	**Very Poor PM2.5 (121-250)**	**Severe PM2.5 (250+)**
2018	44.4	22.2	6.5	0.0
2019	17.6	24.1	35.2	0.0
2020	39.8	23.1	29.6	0.0
2021	21.3	29.6	31.5	0.0
2022	20.4	32.4	29.6	0.9

Table 12: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Sept - 31 Dec) in Punjab

Year	**Moderately polluted PM2.5 (61-90)**	**Poor PM2.5 (91-120)**	**Very Poor PM2.5 (121-250)**	**Severe PM2.5 (250+)**
2018	7.4	13.9	61.1	1.9
2019	13.9	10.2	44.4	20.4
2020	7.4	10.2	55.6	26.9
2021	9.3	5.6	51.9	22.2
2022	7.4	13.0	53.7	15.7

Table 13: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Sept - 31 Dec) in Haryana

Year	**Moderately polluted PM2.5 (61-90)**	**Poor PM2.5 (91-120)**	**Very Poor PM2.5 (121-250)**	**Severe PM2.5 (250+)**
2018	3.7	7.4	45.4	35.2
2019	4.6	5.6	35.2	36.1
2020	10.2	7.4	36.1	41.7
2021	6.5	7.4	37.0	32.4
2022	7.4	11.1	52.8	15.7

Table 14: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Sept - 31 Dec) in Uttar Pradesh

Year	Moderately polluted PM2.5 (61-90)	Poor PM2.5 (91-120)	Very Poor PM2.5 (121-250)	Severe PM2.5 (250+)
2018	4.6	11.1	31.5	49.1
2019	6.5	6.5	38.0	35.2
2020	8.3	8.3	37.0	41.7
2021	11.1	7.4	29.6	39.8
2022	5.6	8.3	38.9	35.2

Table 15: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Sept - 31 Dec) in Delhi

Fig 37 to Fig 42 represents the daily maximum PM2.5 during the rabi crop burning season in Punjab from 2018 to 2023.

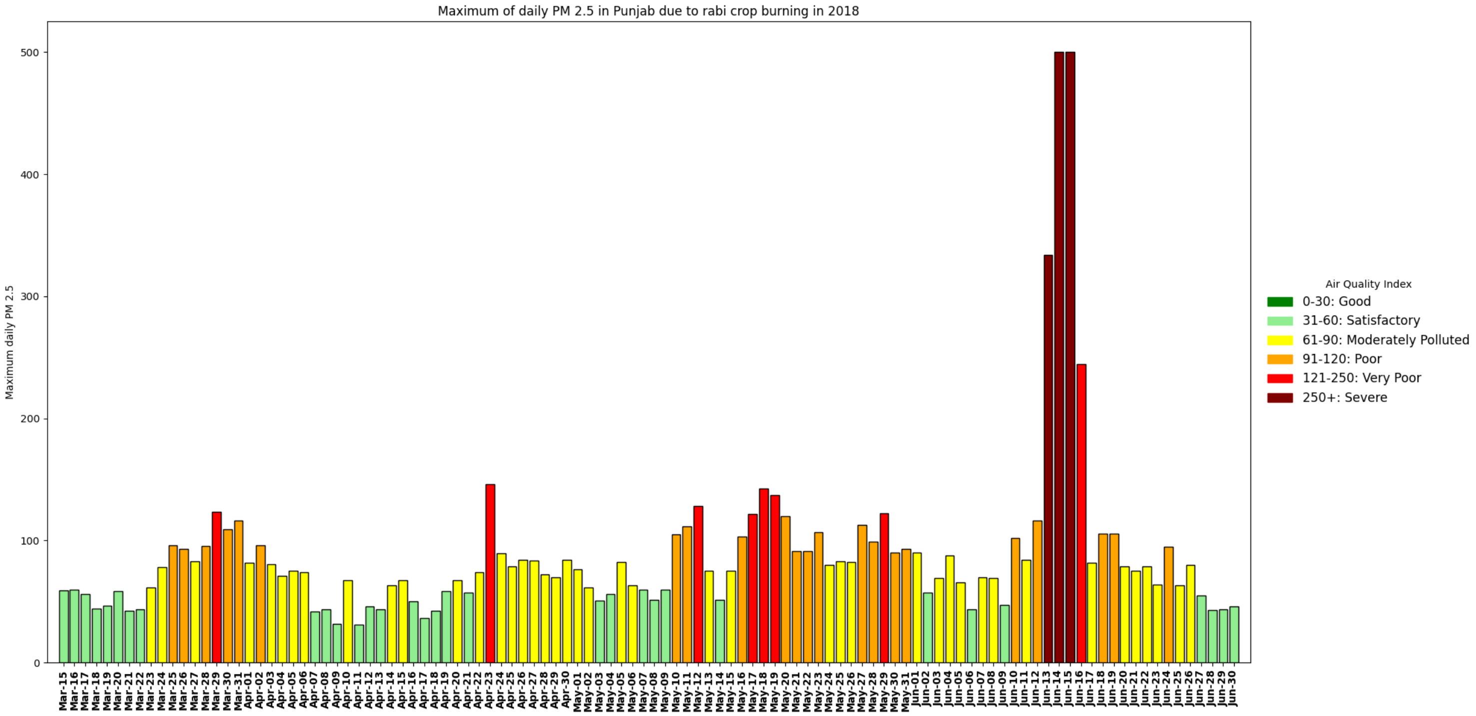


Fig 37: Daily maximum PM2.5 in Punjab from 15 March to 30 June in 2018

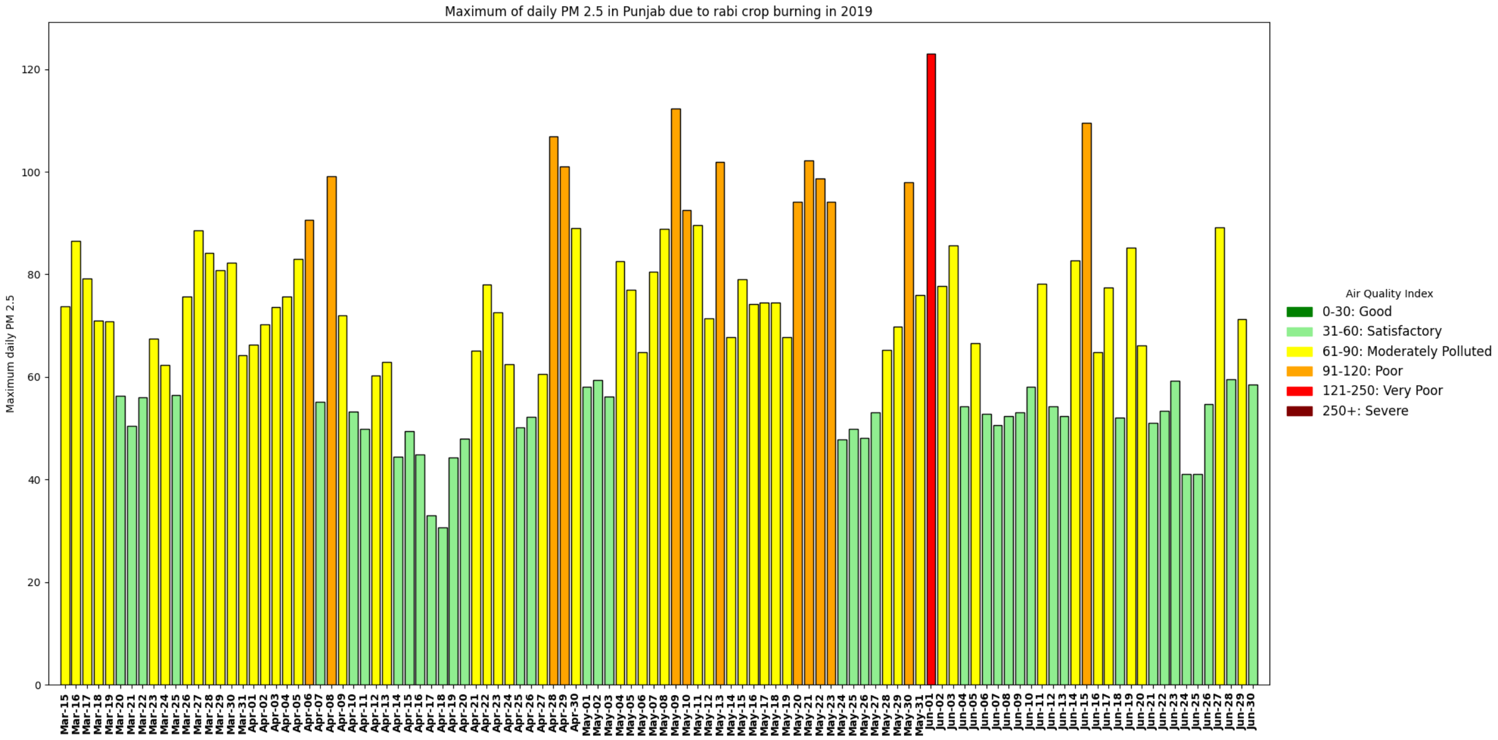


Fig 38: Daily maximum PM2.5 in Punjab from 15 March to 30 June in 2019

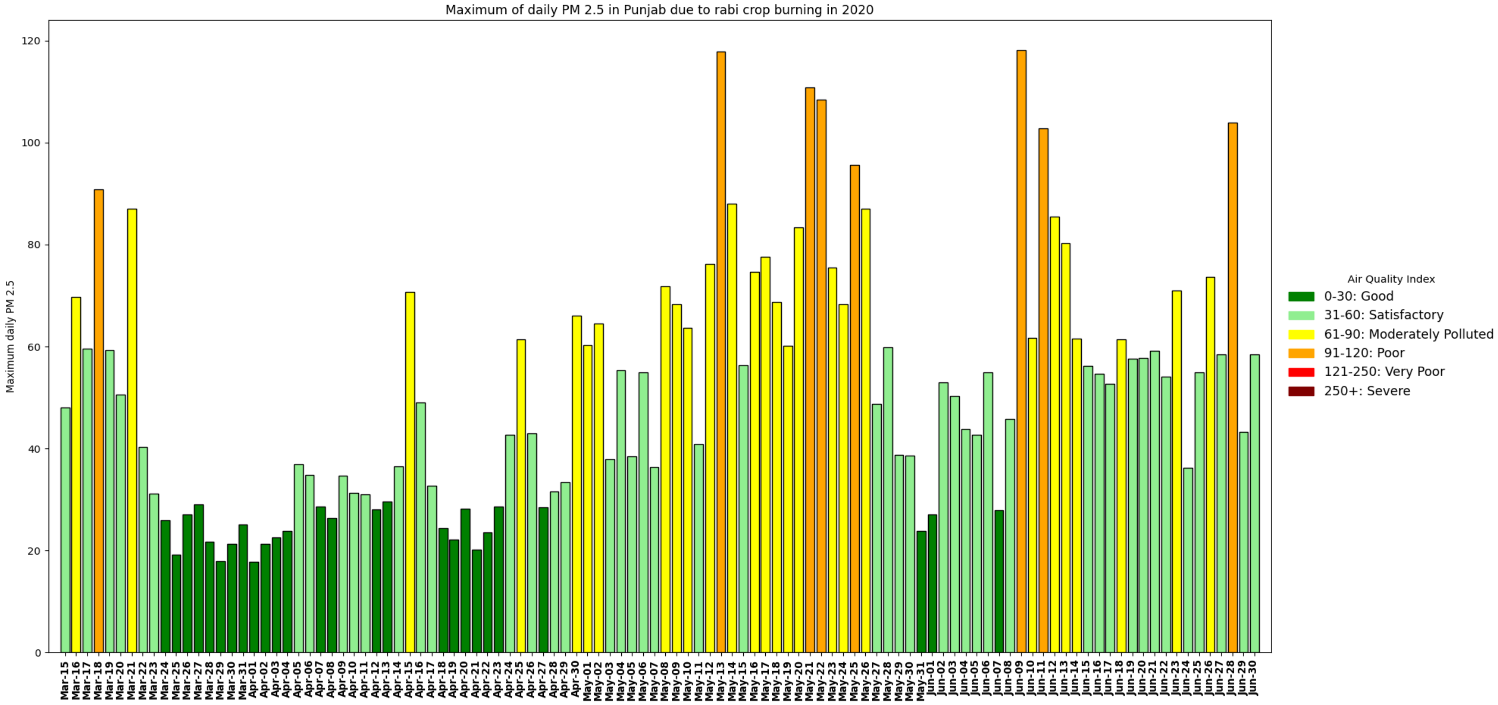


Fig 39: Daily maximum PM2.5 in Punjab from 15 March to 30 June in 2020

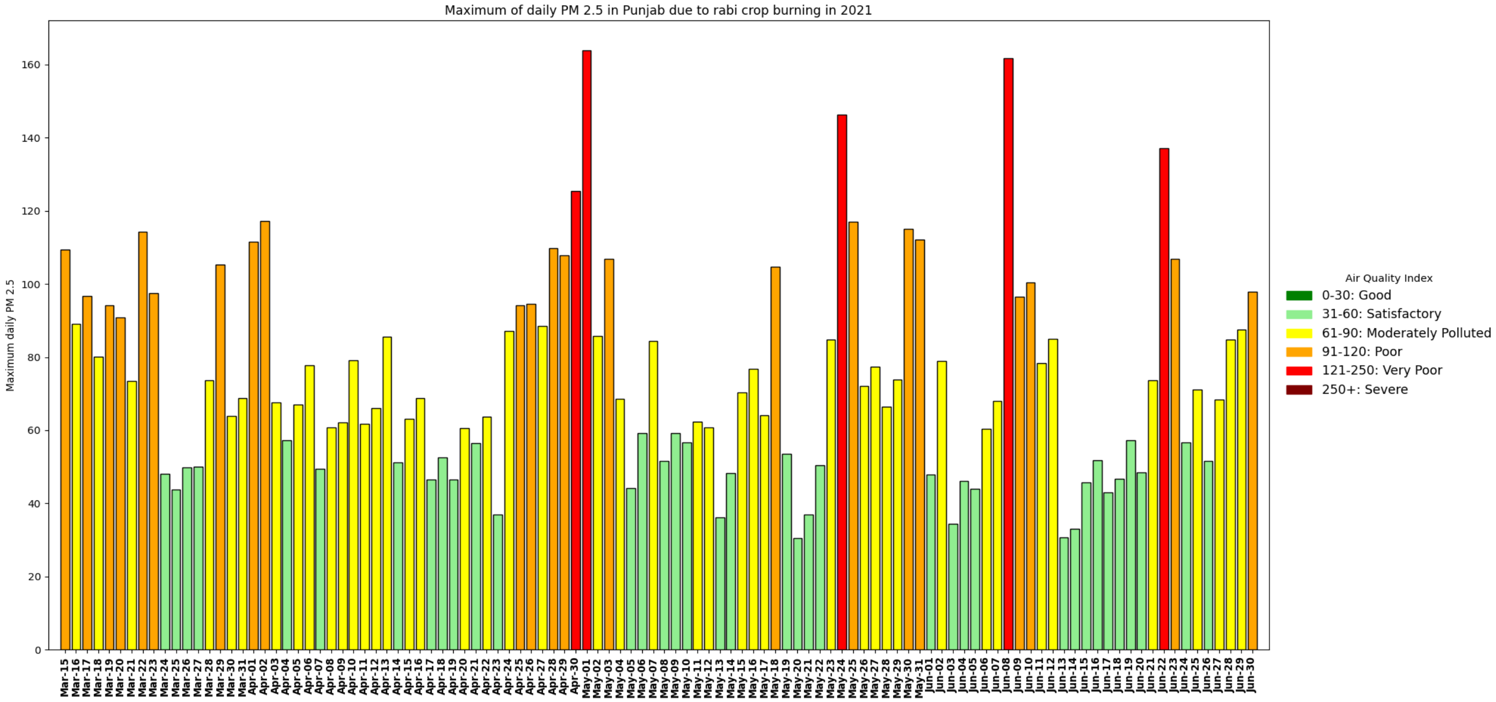


Fig 40: Daily maximum PM2.5 in Punjab from 15 March to 30 June in 2021

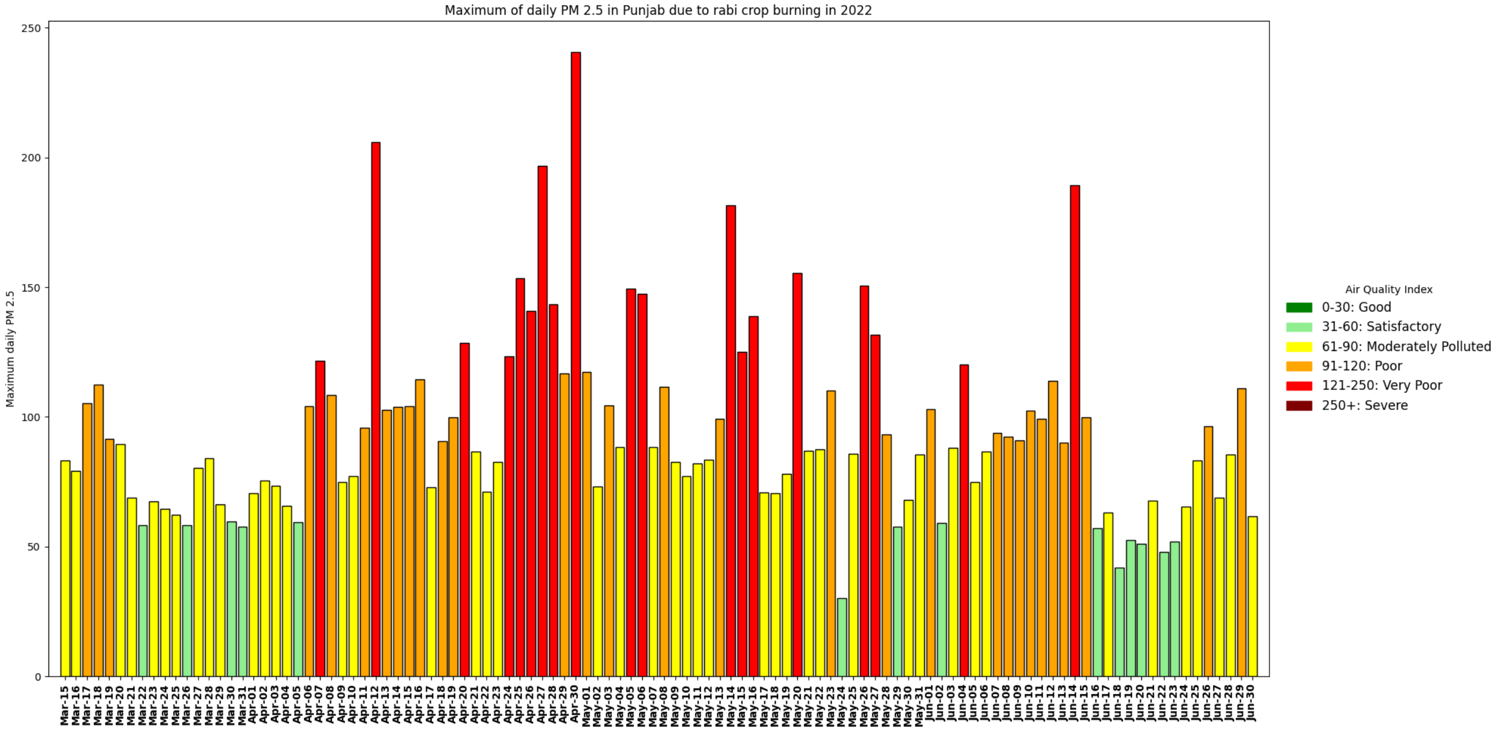


Fig 41: Daily maximum PM2.5 in Punjab from 15 March to 30 June in 2022

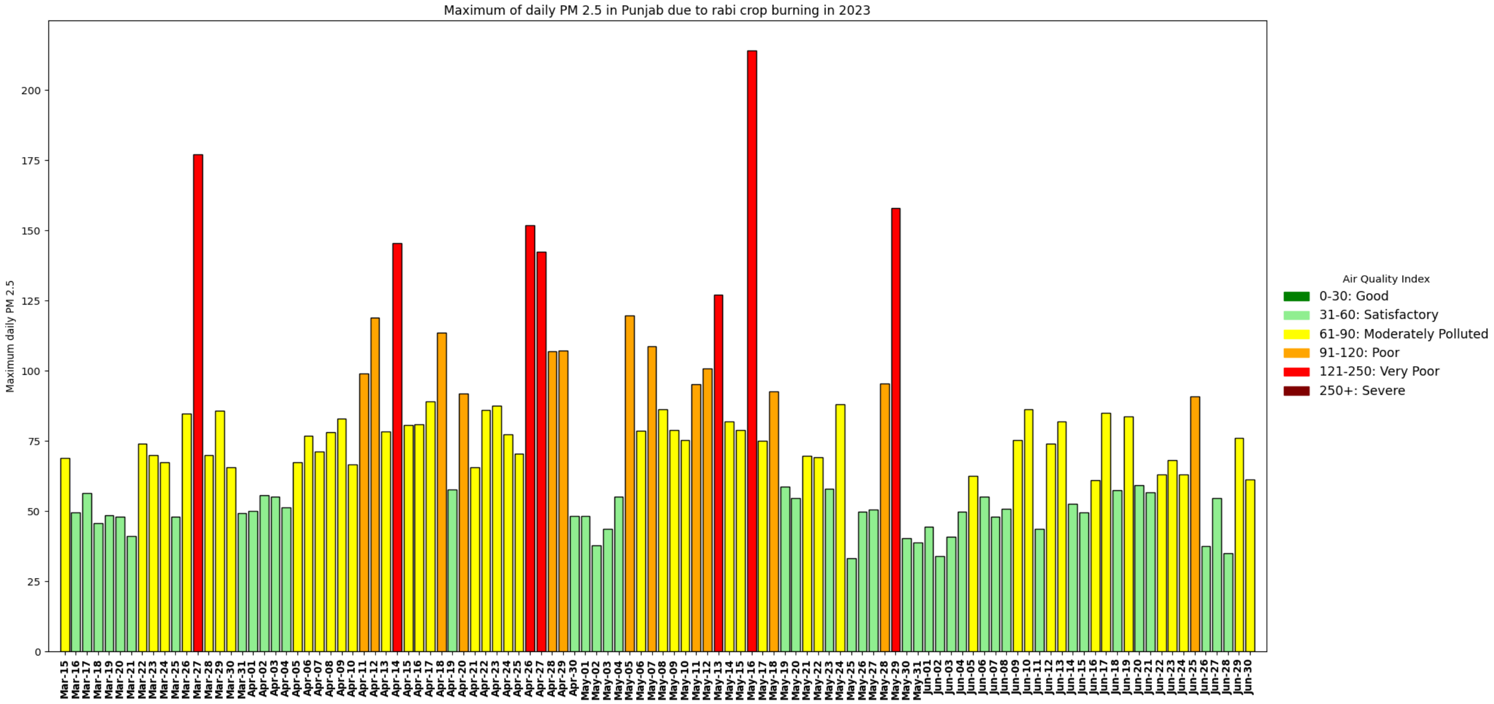


Fig 42: Daily maximum PM2.5 in Punjab from 15 March to 30 June in 2023

Fig 43 to Fig 48 represents the daily maximum PM2.5 during the rabi crop burning season in Haryana from 2018 to 2023.

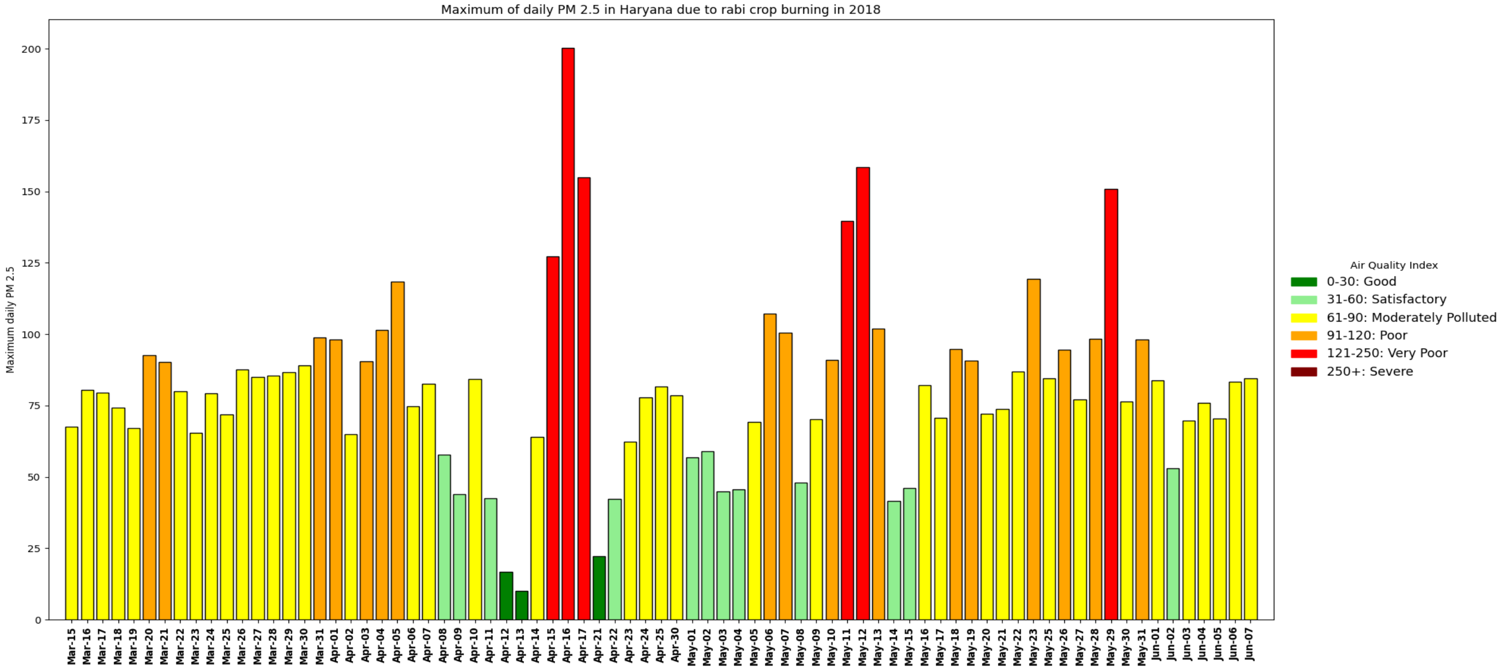


Fig 43: Daily maximum PM2.5 in Haryana from 15 March to 30 June in 2018

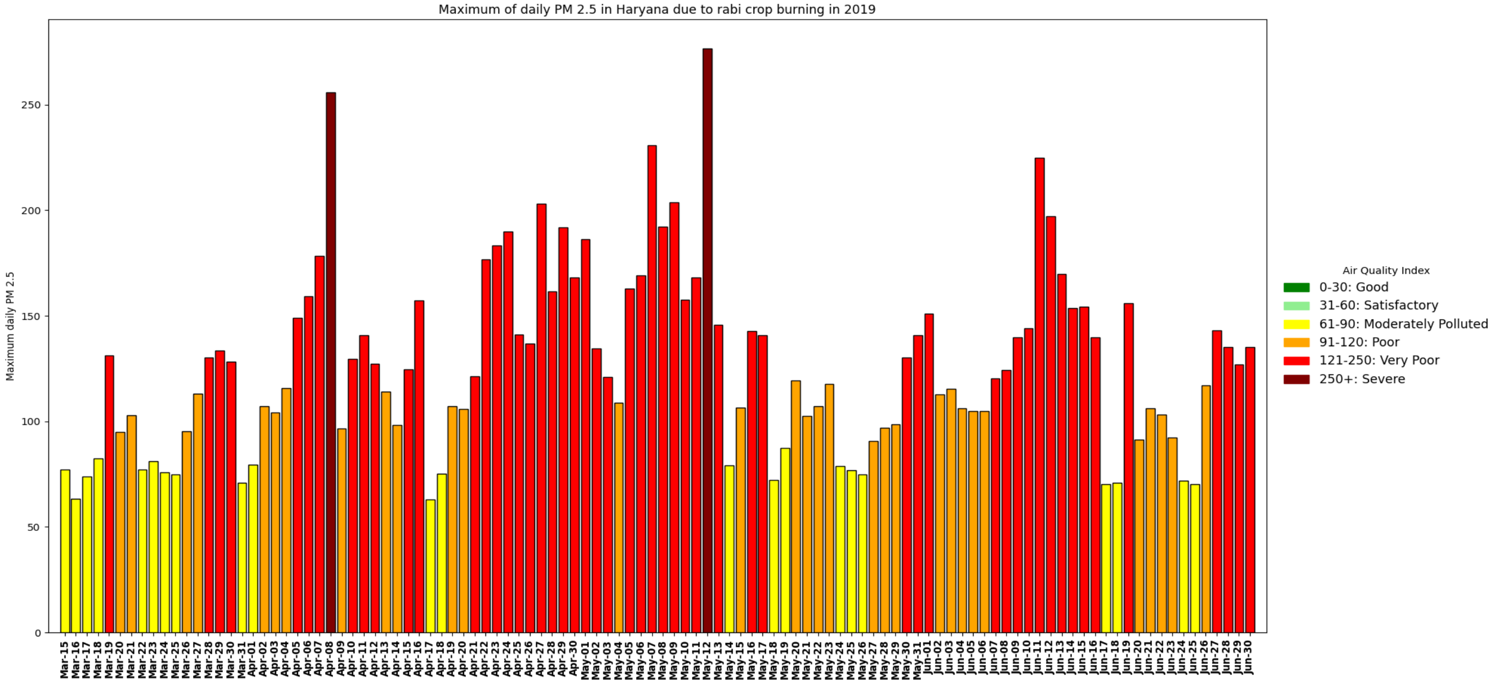


Fig 44: Daily maximum PM2.5 in Haryana from 15 March to 30 June in 2019

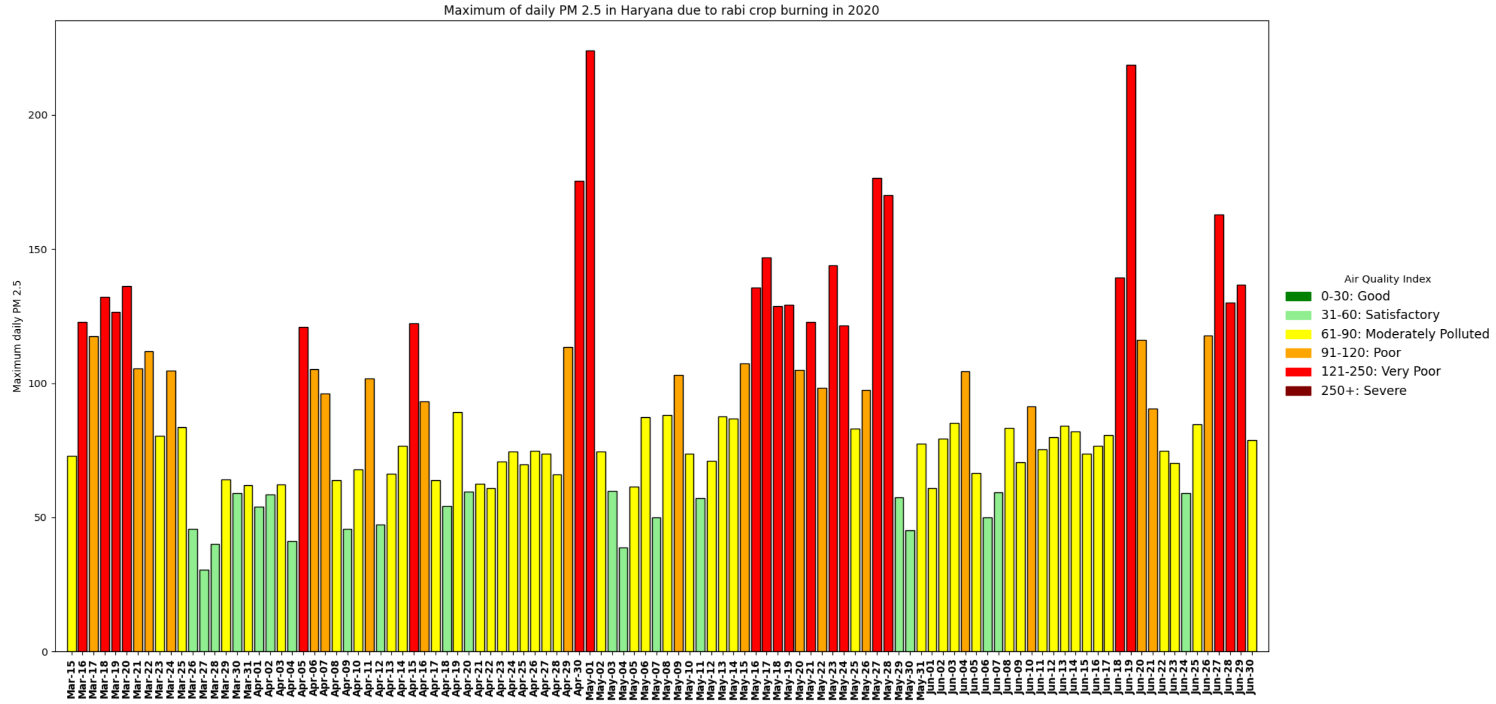


Fig 45: Daily maximum PM2.5 in Haryana from 15 March to 30 June in 2020

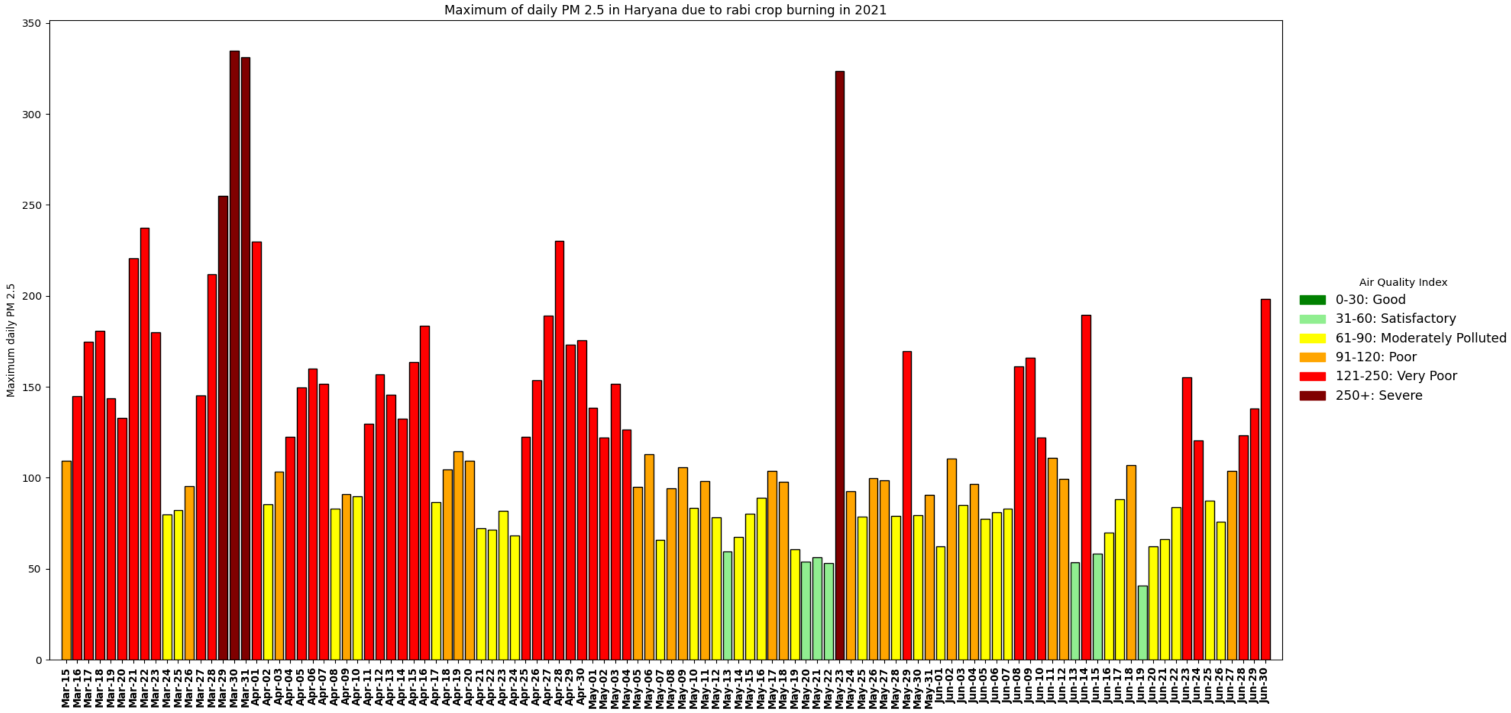


Fig 46: Daily maximum PM2.5 in Haryana from 15 March to 30 June in 2021

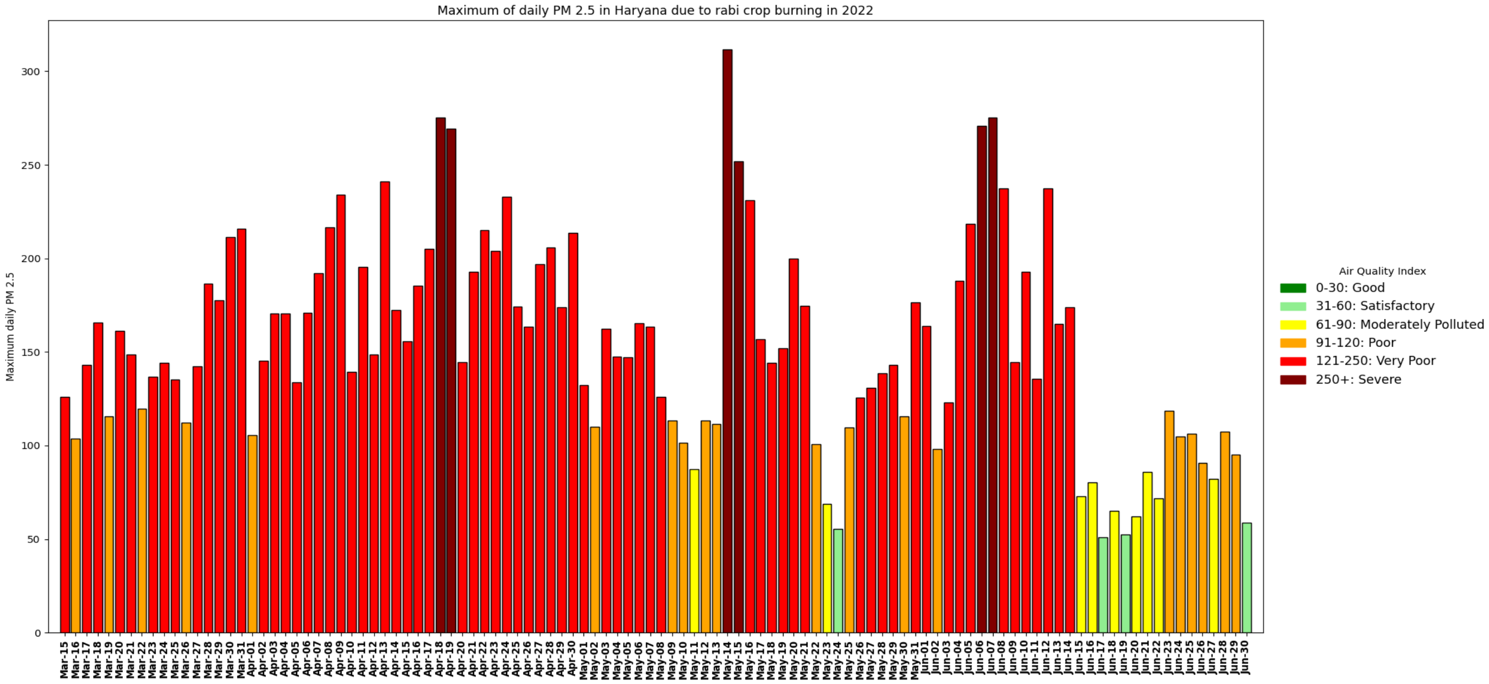


Fig 47: Daily maximum PM2.5 in Haryana from 15 March to 30 June in 2022

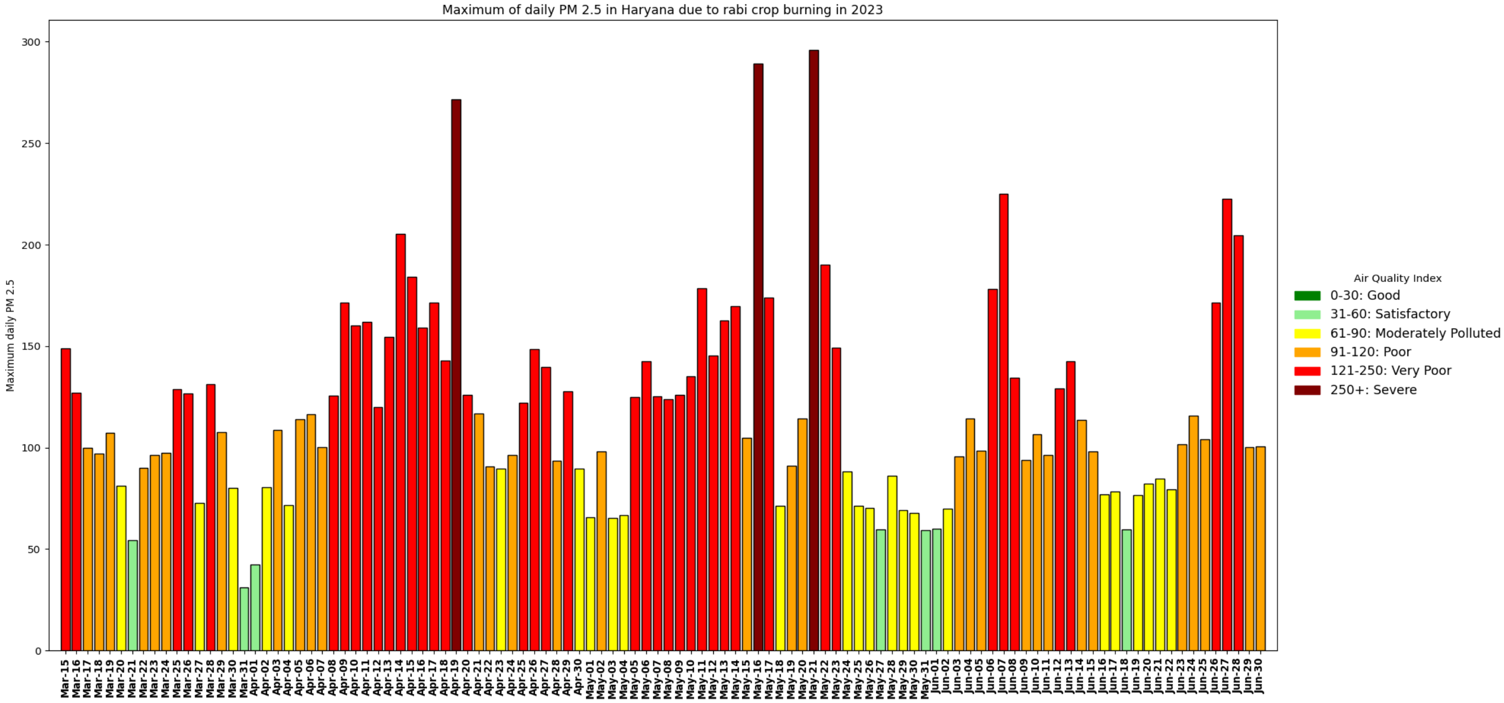


Fig 48: Daily maximum PM2.5 in Haryana from 15 March to 30 June in 2023

Fig 49 to Fig 55 represents the daily maximum PM2.5 during the rabi crop burning season in Uttar Pradesh from 2018 to 2023.

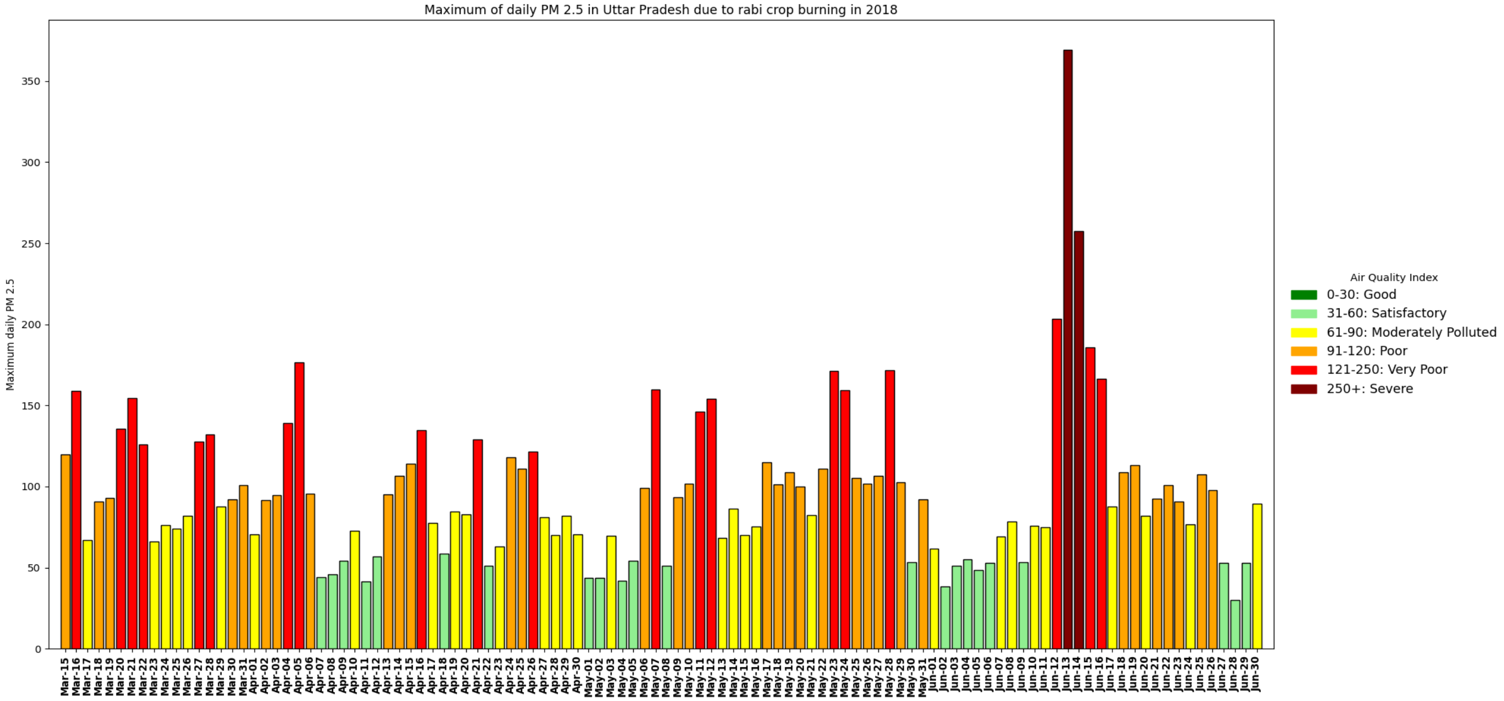


Fig 49: Daily maximum PM2.5 in Uttar Pradesh from 15 March to 30 June in 2018

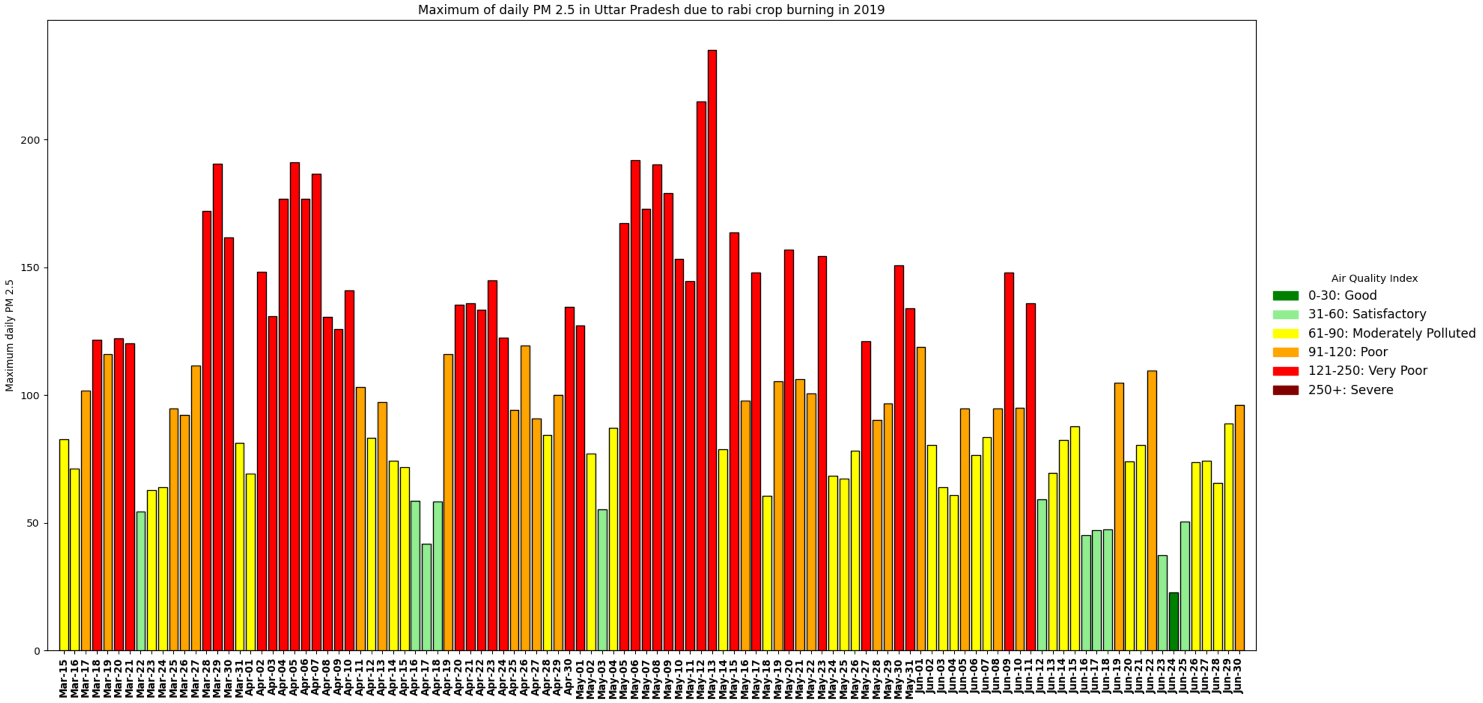


Fig 50: Daily maximum PM2.5 in Uttar Pradesh from 15 March to 30 June in 2019

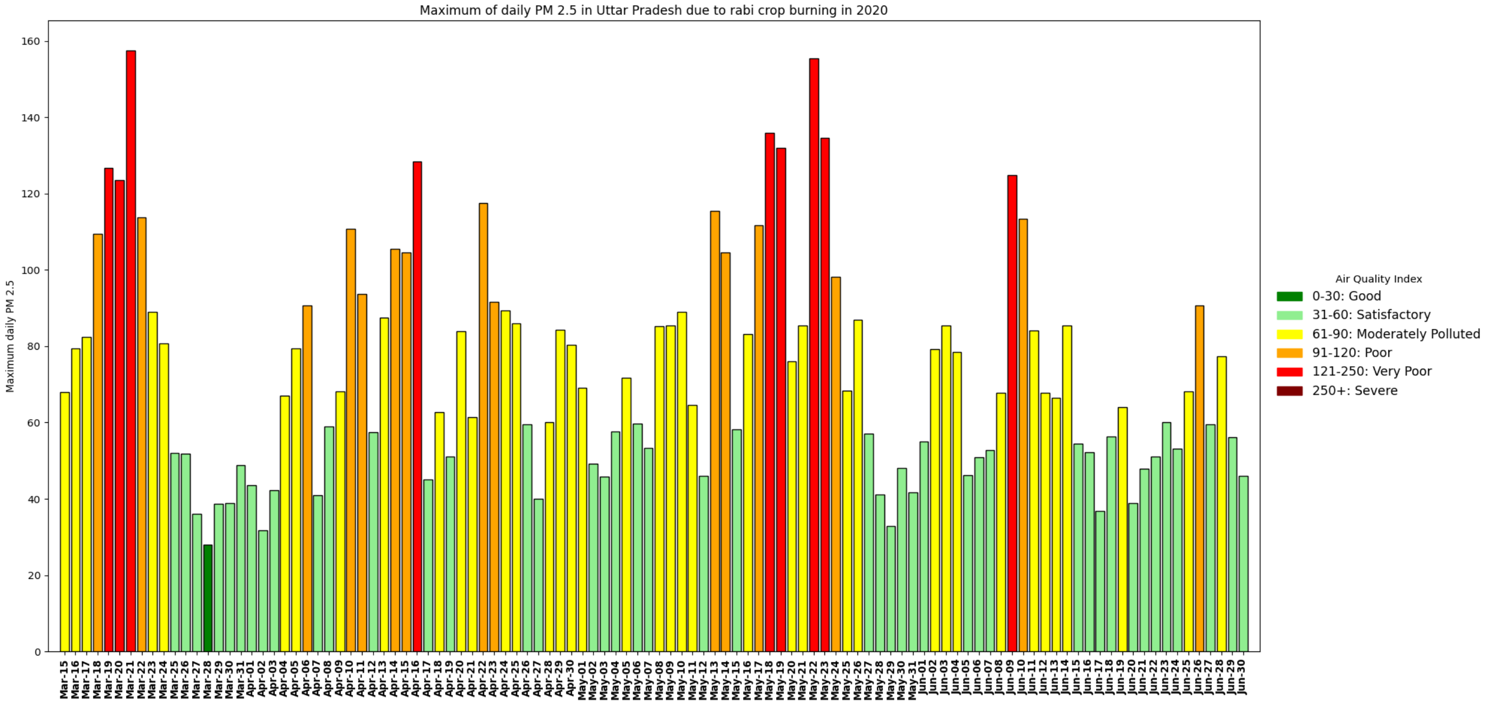


Fig 51: Daily maximum PM2.5 in Uttar Pradesh from 15 March to 30 June in 2020

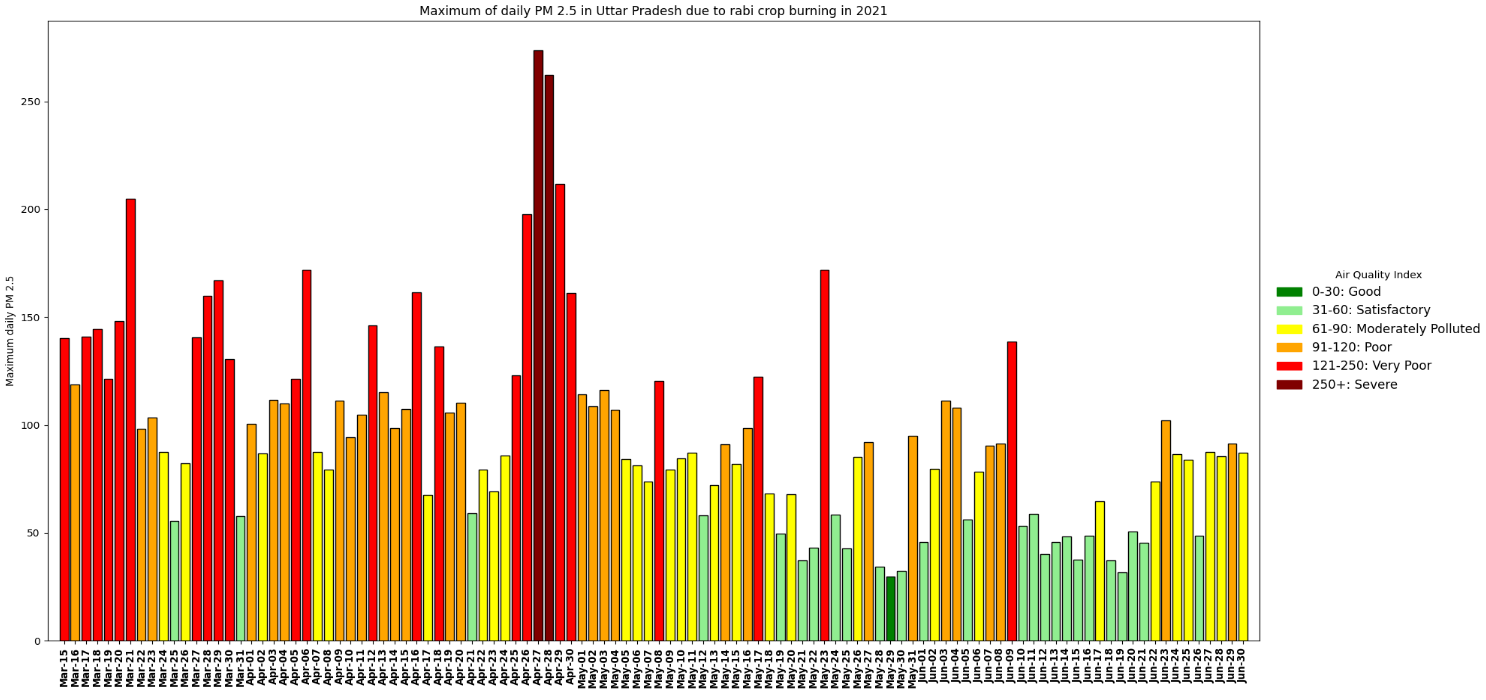


Fig 52: Daily maximum PM2.5 in Uttar Pradesh from 15 March to 30 June in 2021

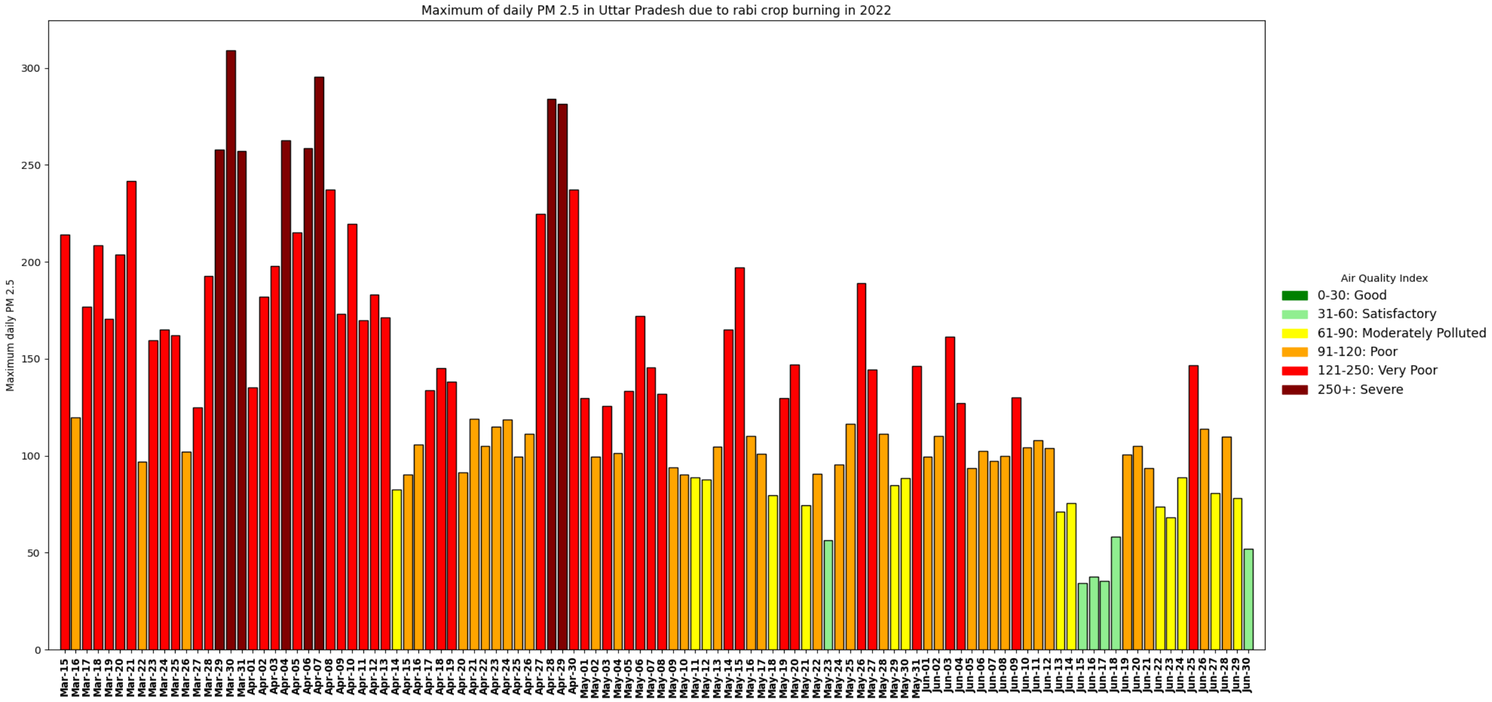


Fig 53: Daily maximum PM2.5 in Uttar Pradesh from 15 March to 30 June in 2022

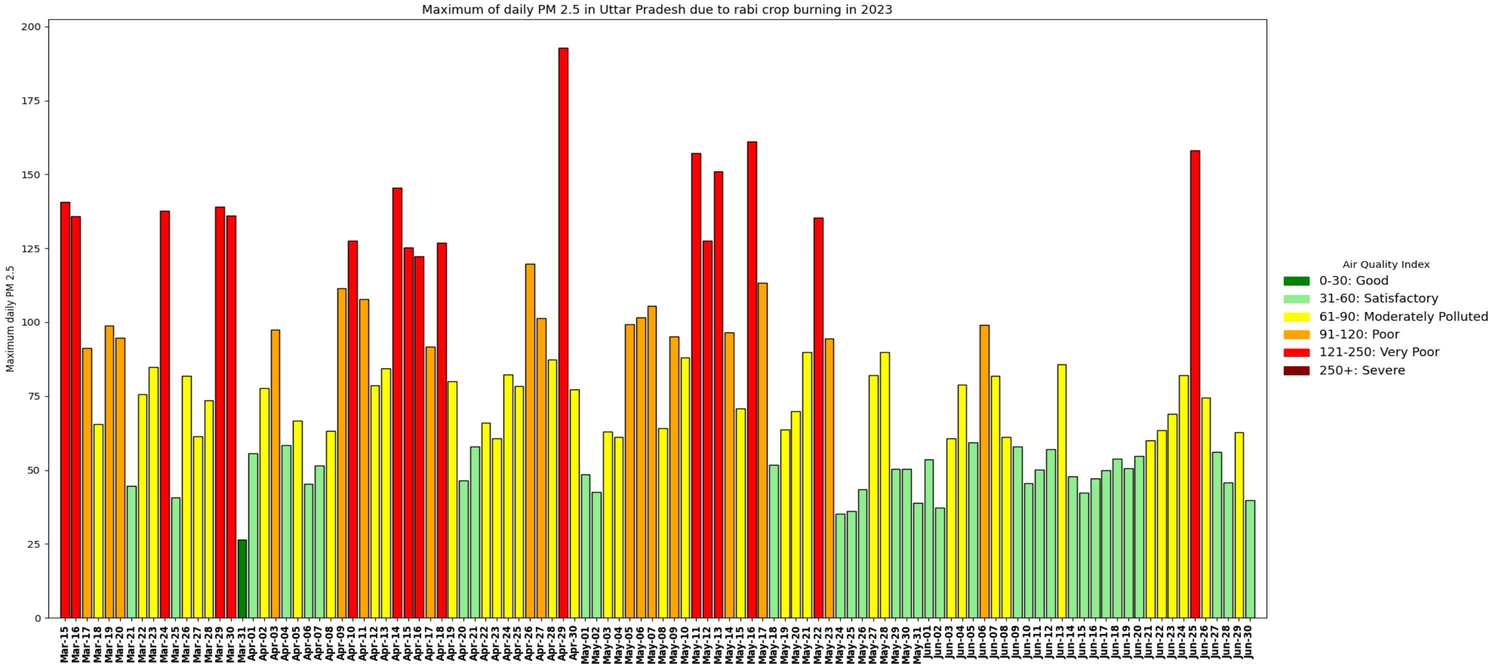


Fig 54: Daily maximum PM2.5 in Uttar Pradesh from 15 March to 30 June in 2023

Fig 55 to Fig 60 represents the daily maximum PM2.5 during the rabi crop burning season in Delhi from 2018 to 2023**.**

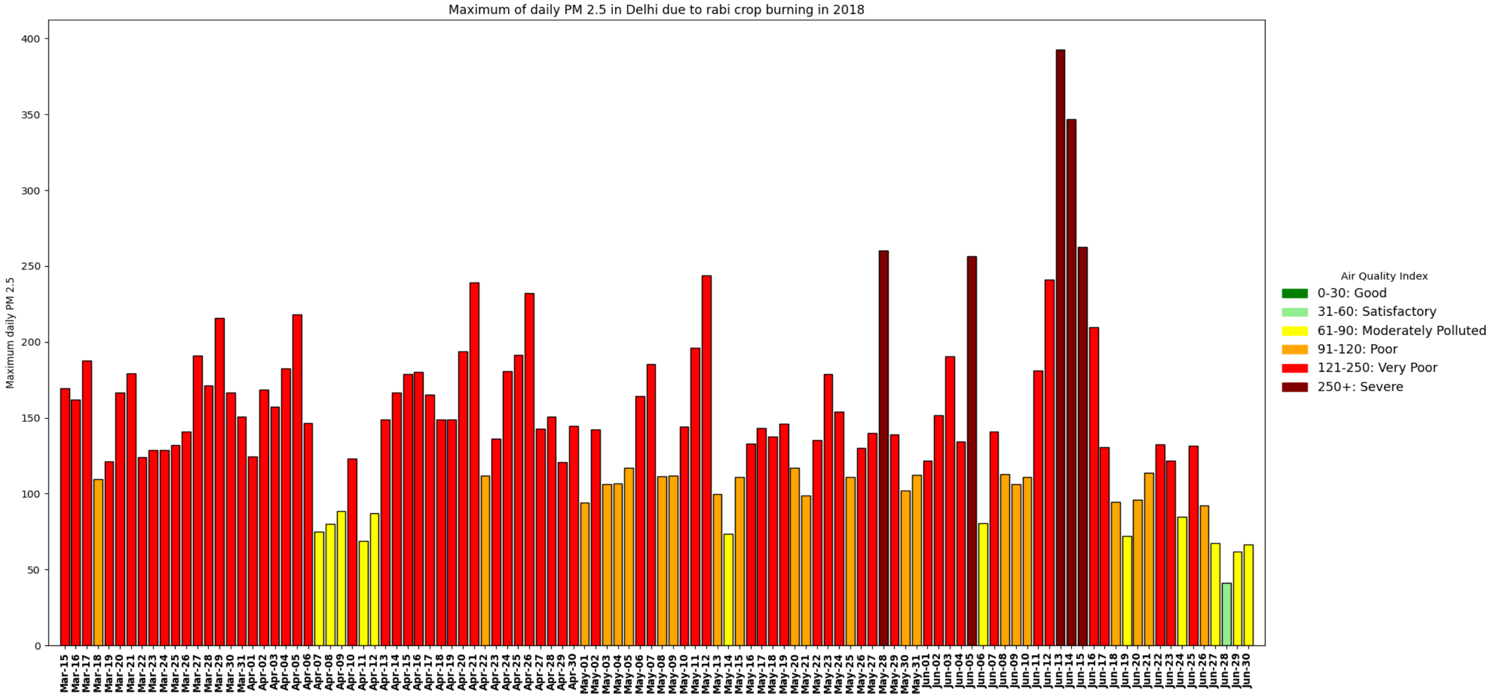


Fig 55: Daily maximum PM2.5 in Delhi from 15 March to 30 June in 2018

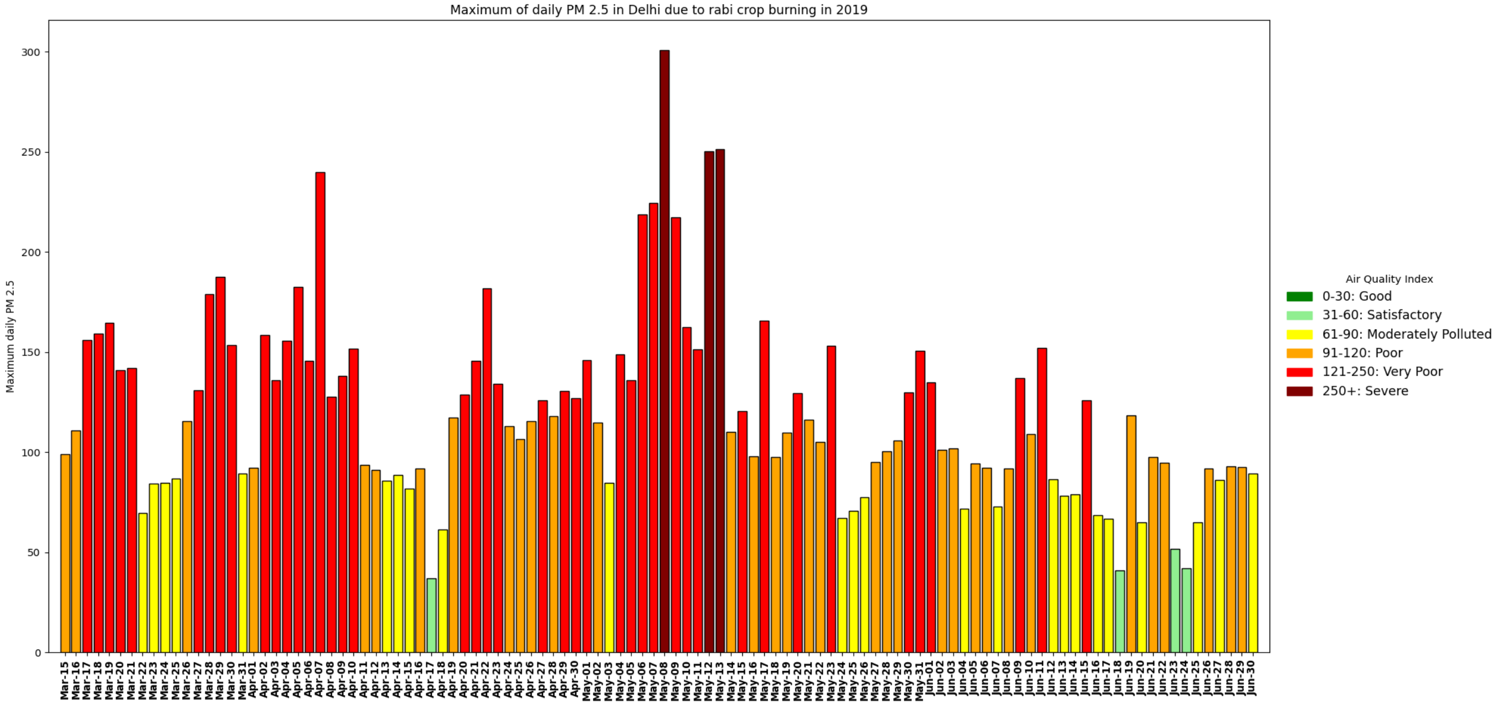


Fig 56: Daily maximum PM2.5 in Delhi from 15 March to 30 June in 2019

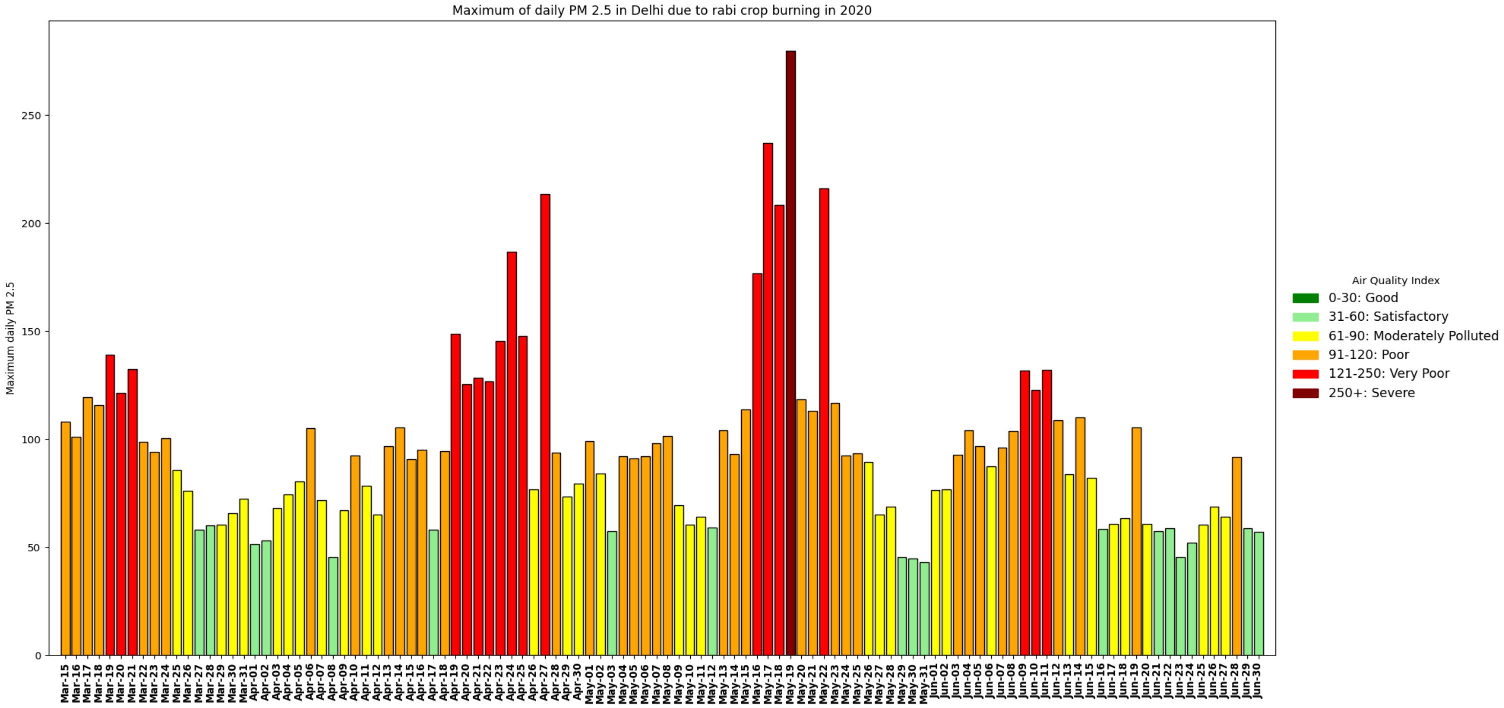


Fig 57: Daily maximum PM2.5 in Delhi from 15 March to 30 June in 2020

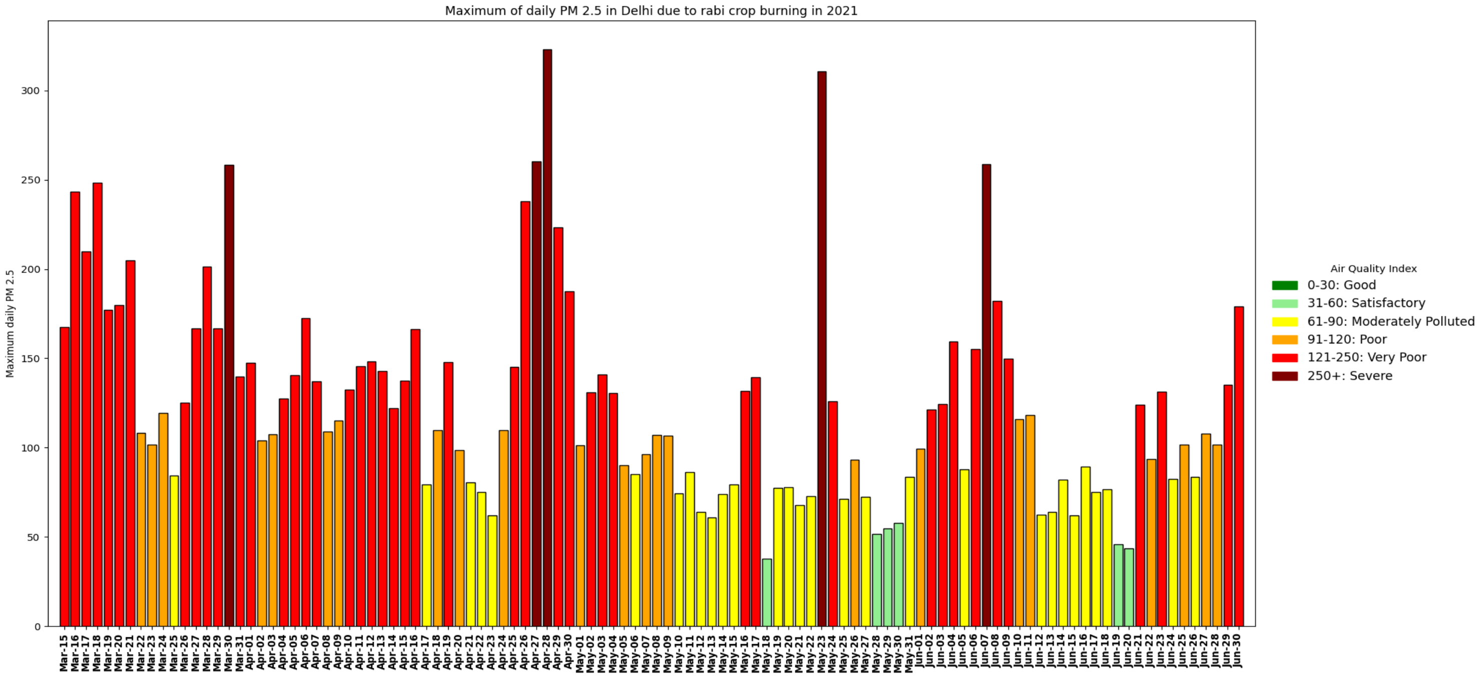


Fig 58: Daily maximum PM2.5 in Delhi from 15 March to 30 June in 2021

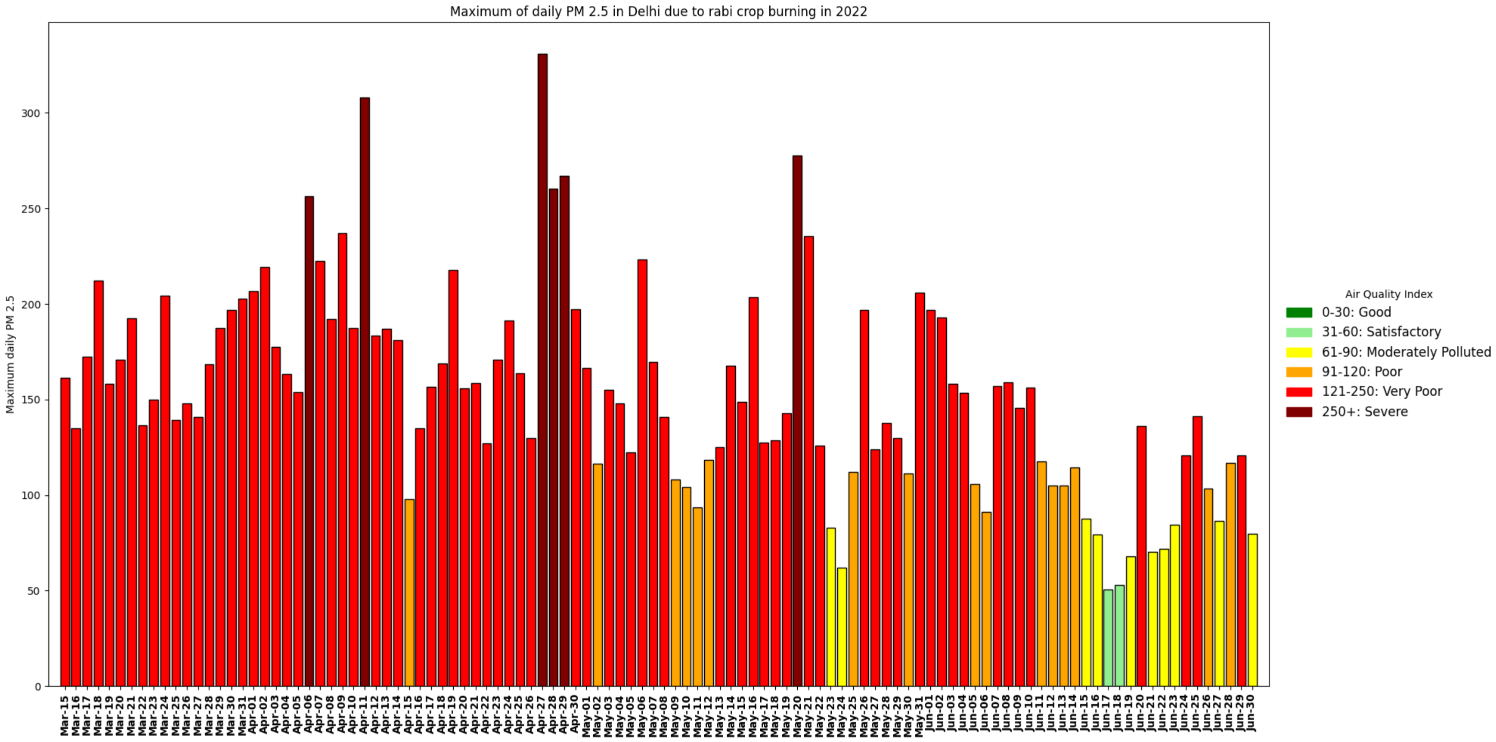


Fig 59: Daily maximum PM2.5 in Delhi from 15 March to 30 June in 2022

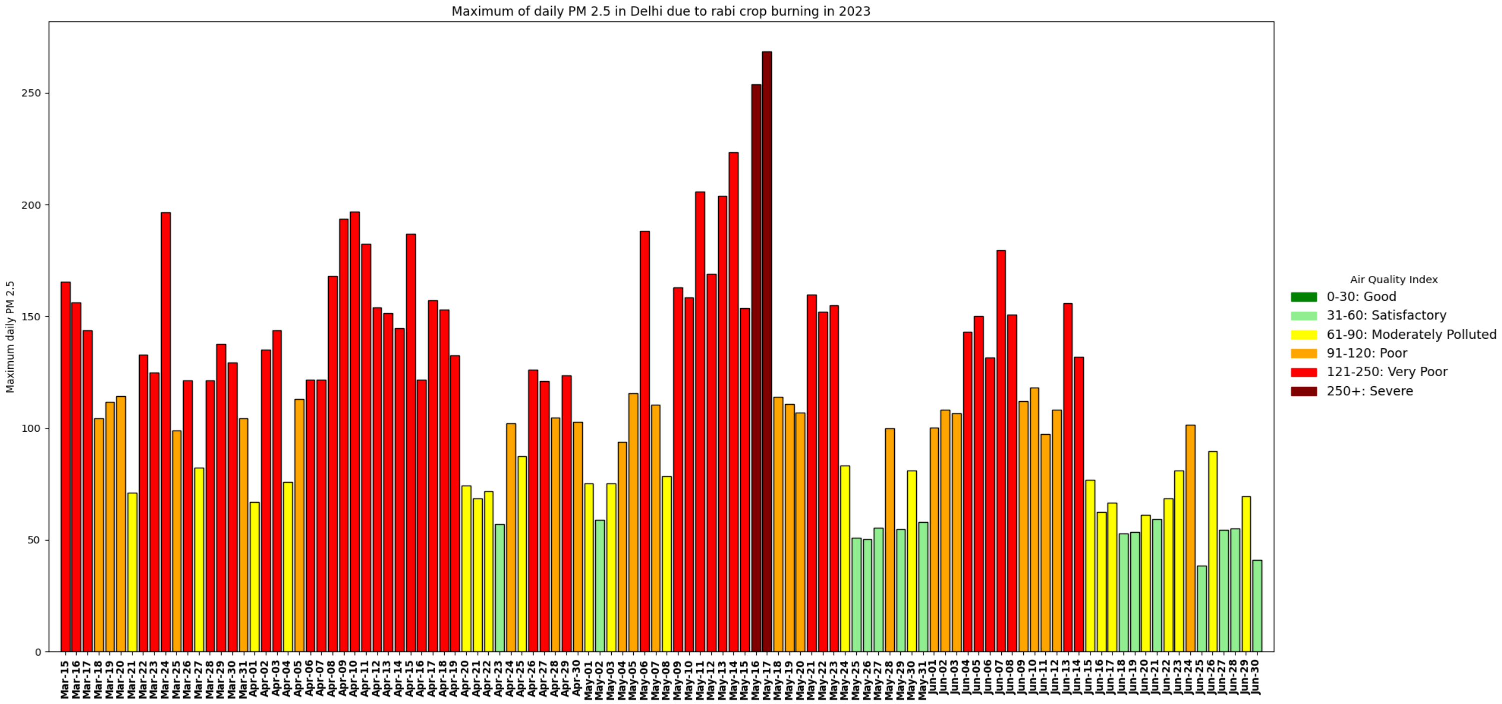


Fig 60: Daily maximum PM2.5 in Delhi from 15 March to 30 June in 2023

Similarly, summarising the findings from Figs 37 to Fig 60, the percentage of days during which the maximum PM2.5 air quality levels fell into the categories of moderately polluted, poor, very poor and severe. We analyzed a total of 106 days, spanning from 15 March to 30 June (rabi crop burning), for each state and each year from 2018 to 2023.

Year	**Moderately polluted PM2.5 (61-90)**	**Poor PM2.5 (91-120)**	**Very Poor PM2.5 (121-250)**	**Severe PM2.5 (250+)**
2018	39.8	20.4	7.4	2.8
2019	50.0	12.0	0.9	0.0
2020	25.0	7.4	0.0	0.0
2021	40.7	20.4	4.6	0.0
2022	41.7	27.8	17.6	0.0
2023	42.6	12.0	6.5	0.0

Table 16: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Mar - 30 Jun) in Punjab

Year	Moderately polluted PM2.5 (61-90)	Poor PM2.5 (91-120)	Very Poor PM2.5 (121-250)	Severe PM2.5 (250+)
2018	36.1	15.7	5.6	0.0
2019	20.4	28.7	49.1	1.9
2020	43.5	17.6	20.4	0.0
2021	29.6	22.2	38.0	3.7
2022	8.3	18.5	63.9	5.6
2023	22.2	29.6	38.9	2.8

Table 17: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Mar - 30 Jun) in Haryana

Year	Moderately polluted PM2.5 (61-90)	Poor PM2.5 (91-120)	Very Poor PM2.5 (121-250)	Severe PM2.5 (250+)
2018	28.7	30.6	18.5	1.9
2019	28.7	23.1	37.0	0.0
2020	36.1	13.9	8.3	0.0
2021	26.9	25.9	21.3	1.9
2022	13.0	34.3	39.8	7.4
2023	36.1	15.7	15.7	0.0

Table 18: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Mar - 30 Jun) in Uttar Pradesh

Year	**Moderately polluted PM2.5 (61-90)**	**Poor PM2.5 (91-120)**	**Very Poor PM2.5 (121-250)**	**Severe PM2.5 (250+)**
2018	11.1	20.4	63.0	4.6
2019	22.2	31.5	39.8	2.8
2020	30.6	35.2	16.7	0.9
2021	26.9	21.3	41.7	4.6
2022	9.3	14.8	68.5	5.6
2023	19.4	22.2	43.5	1.9

Table 19: Percentage of days the air quality is moderately polluted, poor, very poor or severe (15 Mar - 30 Jun) in Delhi

Shift in burning time period:

In addition to our primary analysis, we also explored any changes in stubble burning practices from 2018 to 2022. This extra examination aimed to pinpoint specific days during the burning season with the most fire incidents, compared to those with fewer. These visuals also highlighted the distinctions between the rabi and kharif crop burning seasons. Rabi burning occurs from April to May, while kharif burning takes place from October to November. This differentiation is crucial for understanding seasonal patterns in stubble burning, adding valuable context to our comprehensive study of this environmental concern.

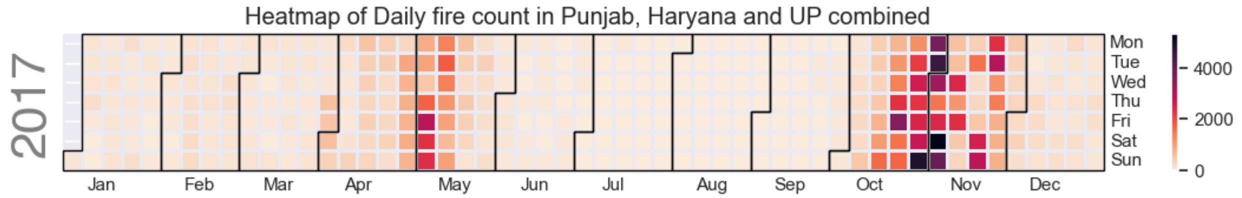


Fig 61: Heatmap of Daily total fire count in Punjab, Haryana and Uttar Pradesh in 2018

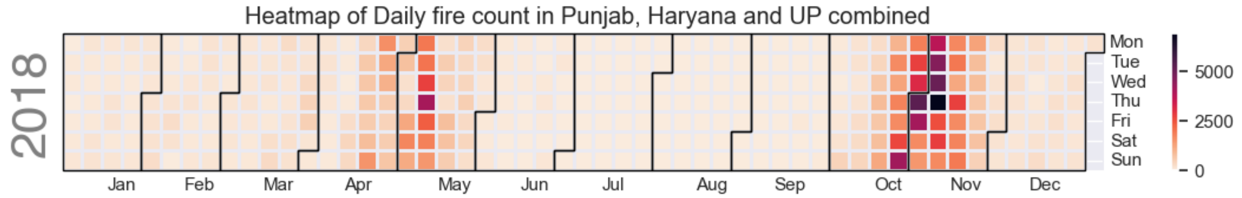


Fig 62: Heatmap of Daily total fire count in Punjab, Haryana and Uttar Pradesh in 2018

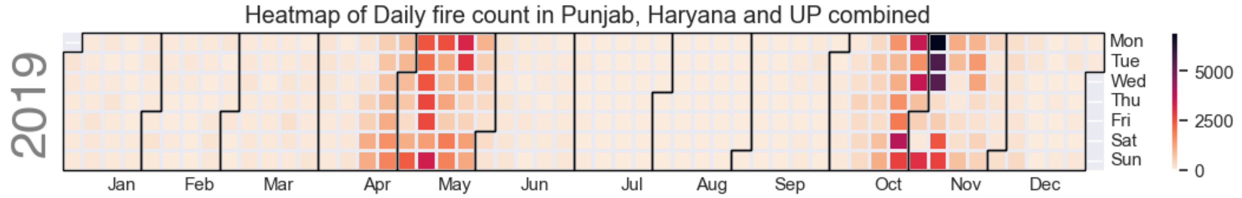


Fig 63: Heatmap of Daily total fire count in Punjab, Haryana and Uttar Pradesh in 2019

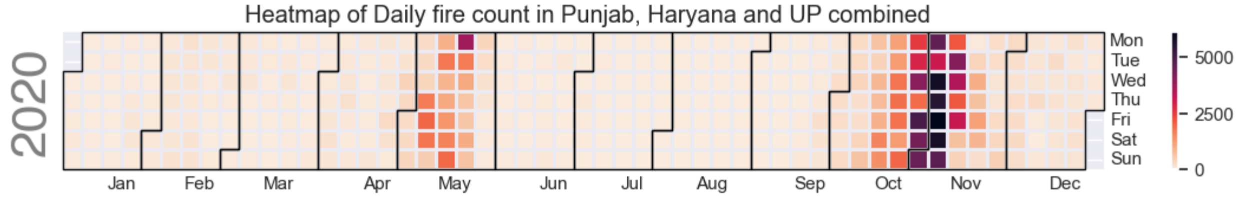


Fig 64: Heatmap of Daily total fire count in Punjab, Haryana and Uttar Pradesh in 2020

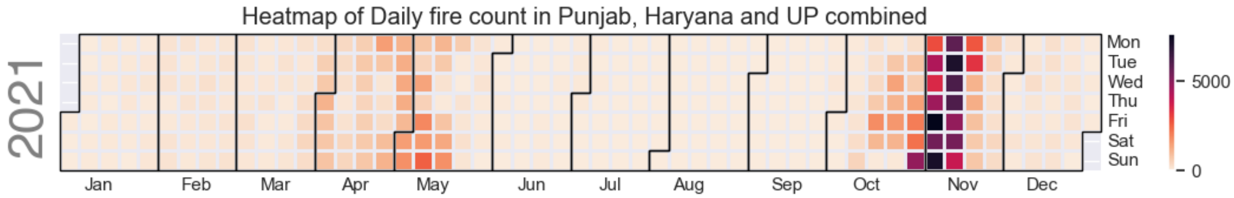


Fig 65: Heatmap of Daily total fire count in Punjab, Haryana and Uttar Pradesh in 2021

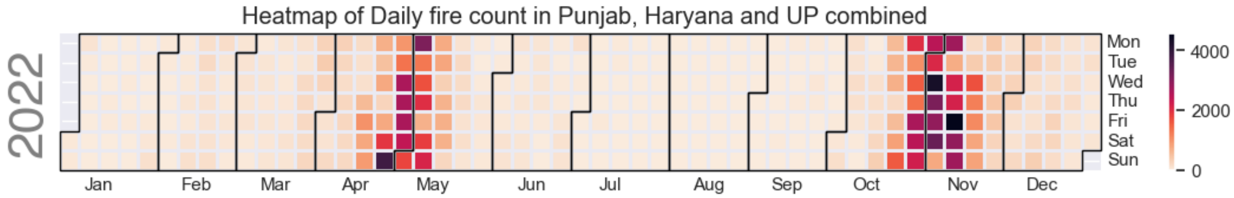


Fig 66: Heatmap of Daily total fire count in Punjab, Haryana and Uttar Pradesh in 2022

We further wanted to understand the energy radiation due to stubble burning as well. We graphed the Fire Radiative Power (FRP) from the fire data for both the crop burning season from 2018 to 2023.

Figs 67 to Fig 72 represents the maximum FRP in Punjab from 15 September to 31 December (Kharif crop burning) for 2018-2022

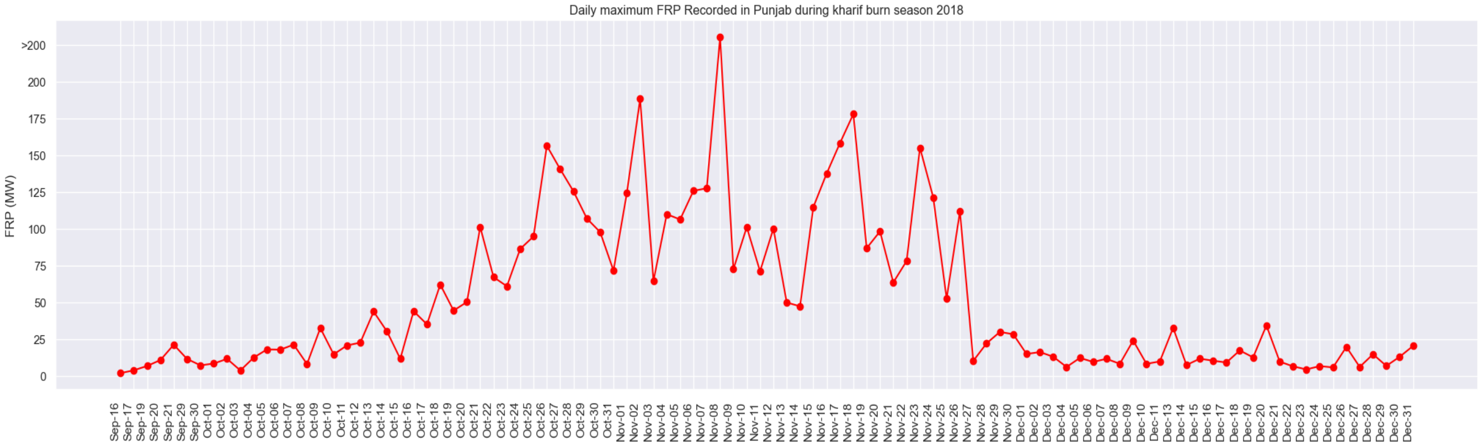


Fig 67: Daily maximum FRP in Punjab from 15 September to 31 December in 2018

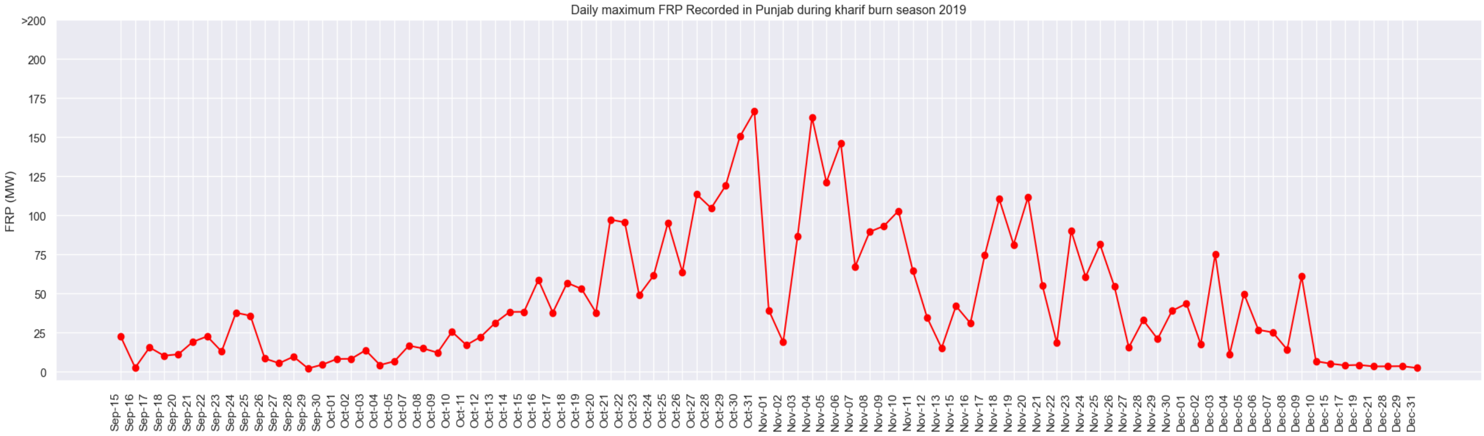


Fig 68: Daily maximum FRP in Punjab from 15 September to 31 December in 2019

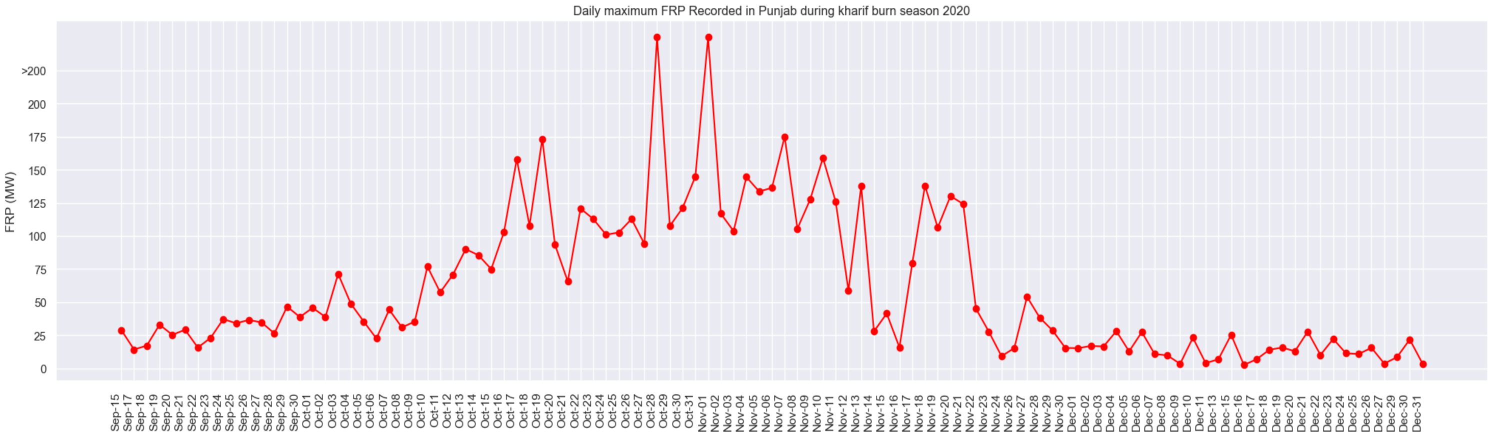


Fig 69: Daily maximum FRP in Punjab from 15 September to 31 December in 2020

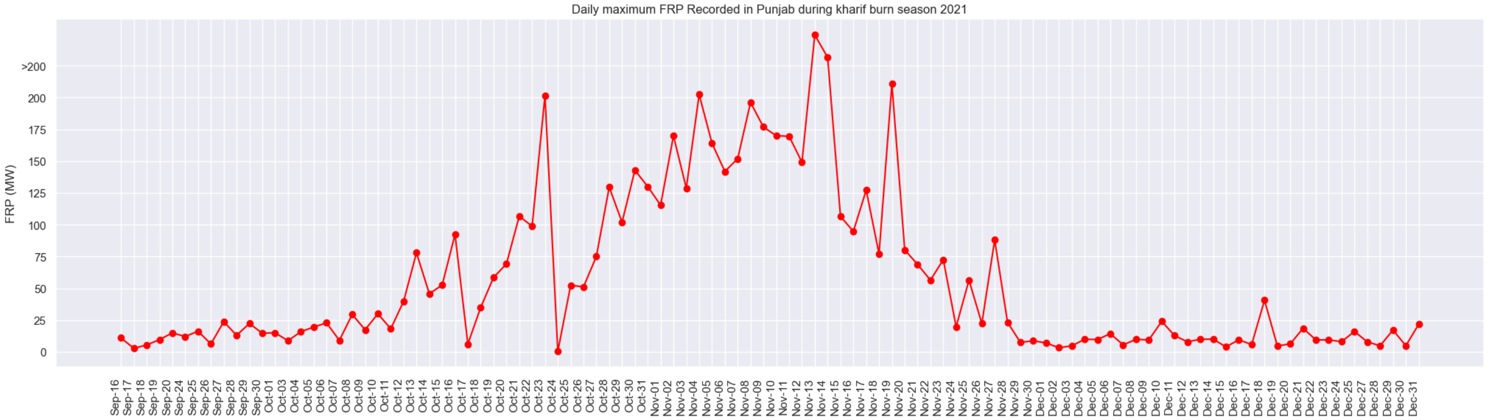


Fig 70: Daily maximum FRP in Punjab from 15 September to 31 December in 2021

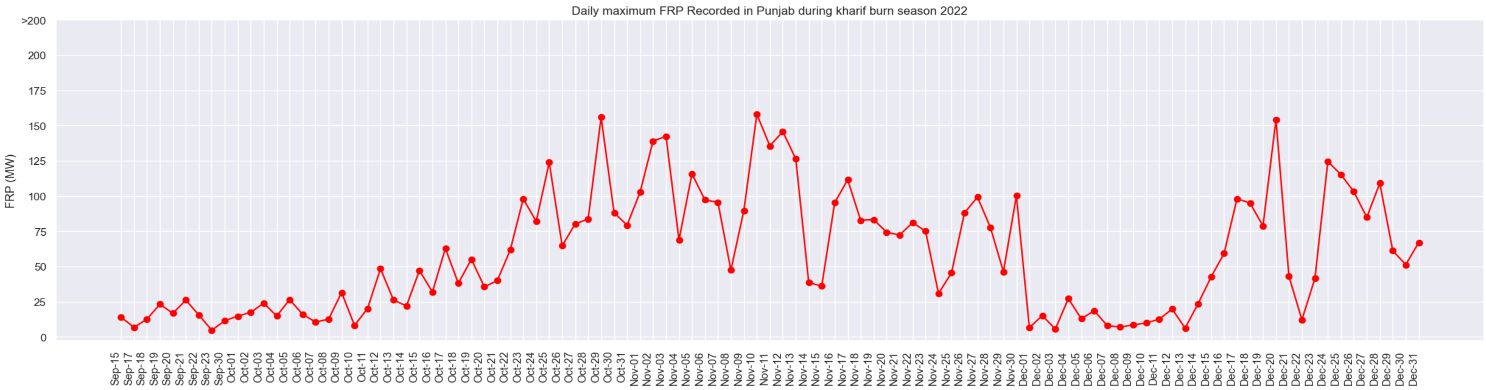


Fig 71: Daily maximum FRP in Punjab from 15 September to 31 December in 2022

Figs 72 to Fig 76 represents the maximum FRP in Haryana from 15 September to 31 December (Kharif crop burning) for 2018-2022

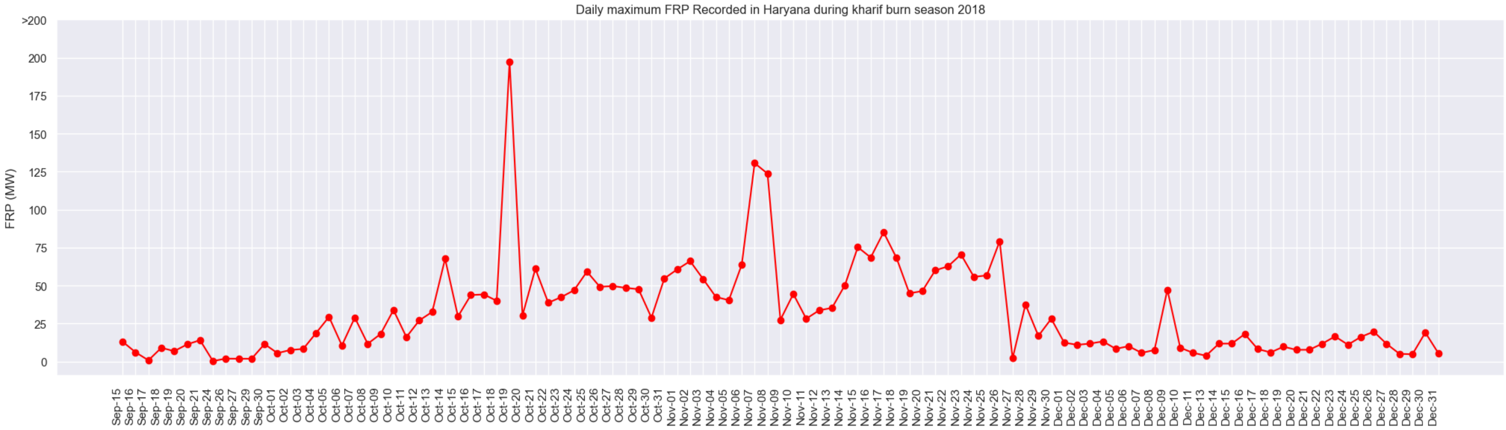


Fig 72: Daily maximum FRP in Haryana from 15 September to 31 December in 2018

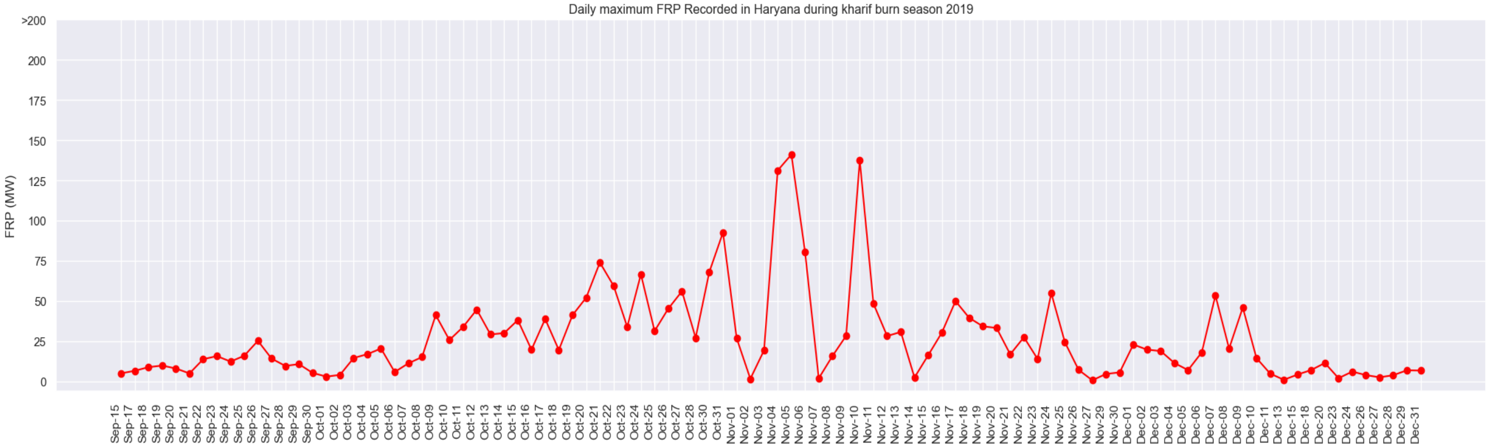


Fig 73: Daily maximum FRP in Haryana from 15 September to 31 December in 2019

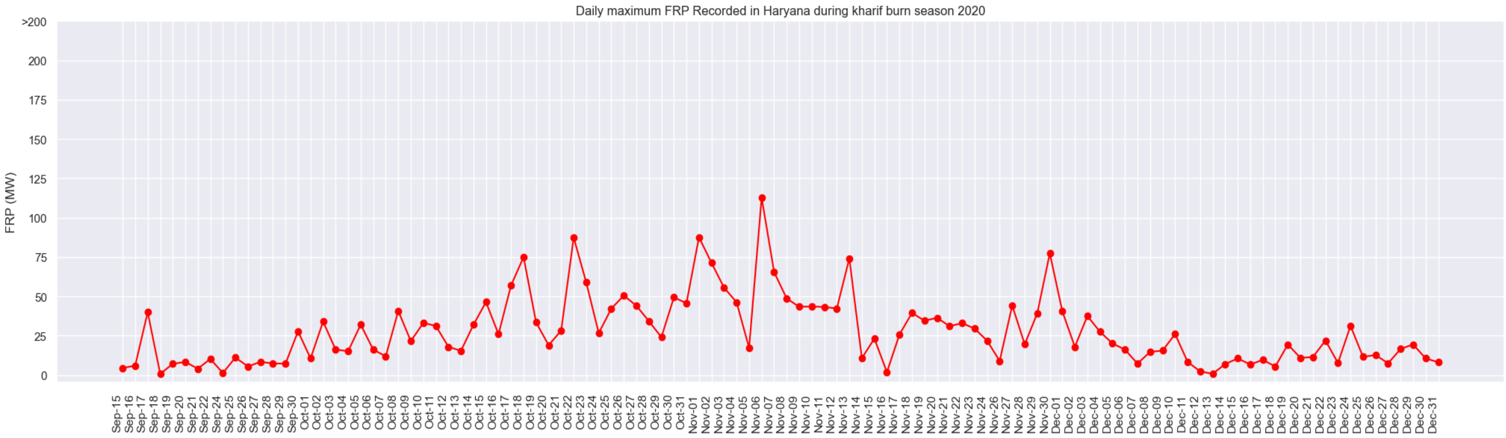


Fig 74: Daily maximum FRP in Haryana from 15 September to 31 December in 2020

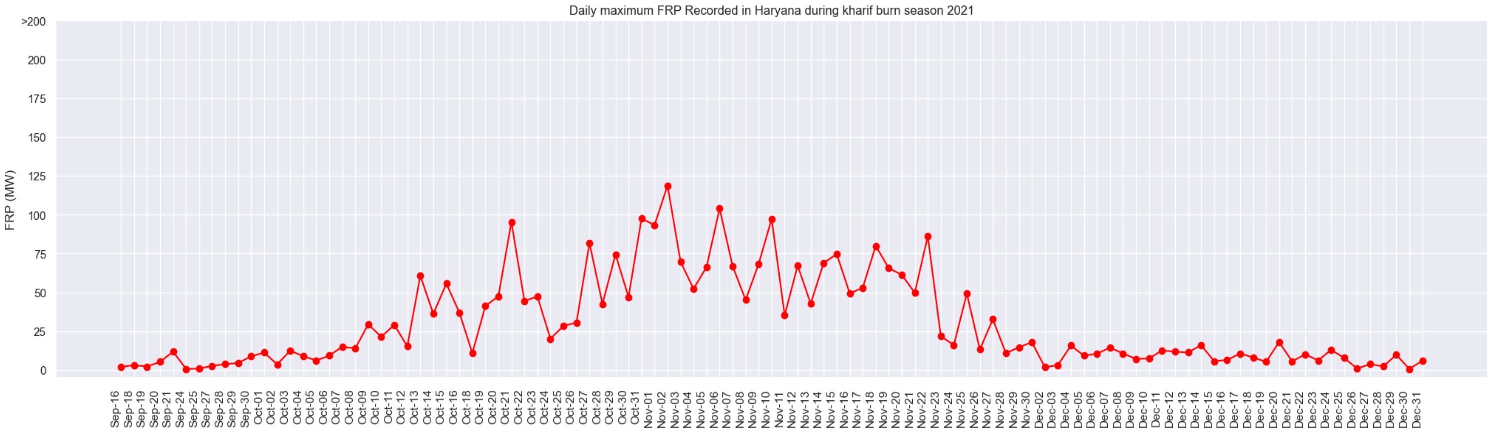


Fig 75: Daily maximum FRP in Haryana from 15 September to 31 December in 2021

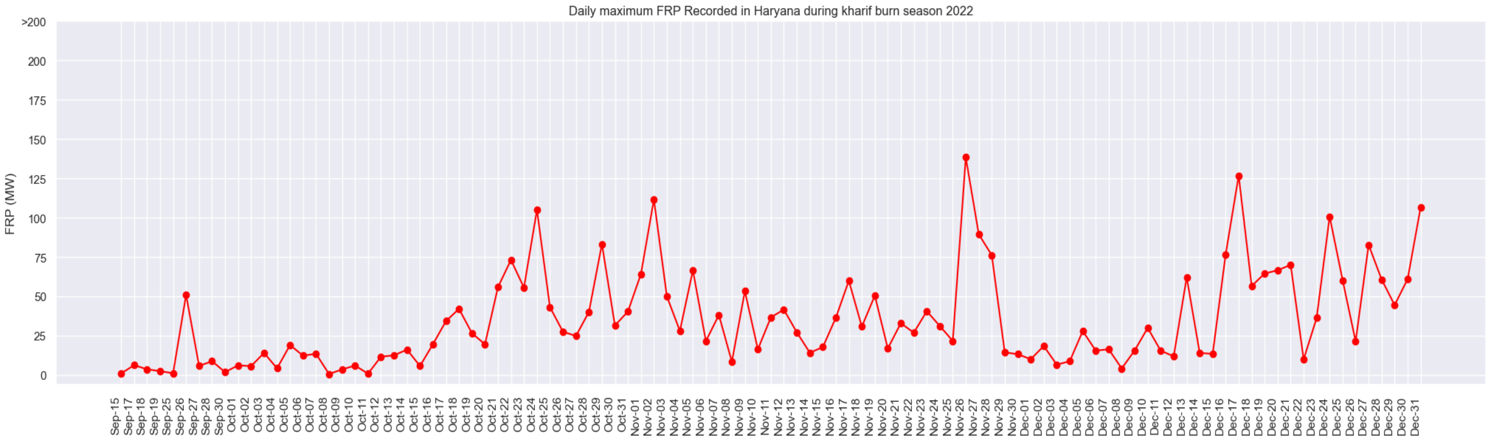


Fig 76: Daily maximum FRP in Haryana from 15 September to 31 December in 2022

Figs 77 to Fig 81 represents the maximum FRP in Uttar Pradesh from 15 September to 31 December (Kharif crop burning) for 2018-2022

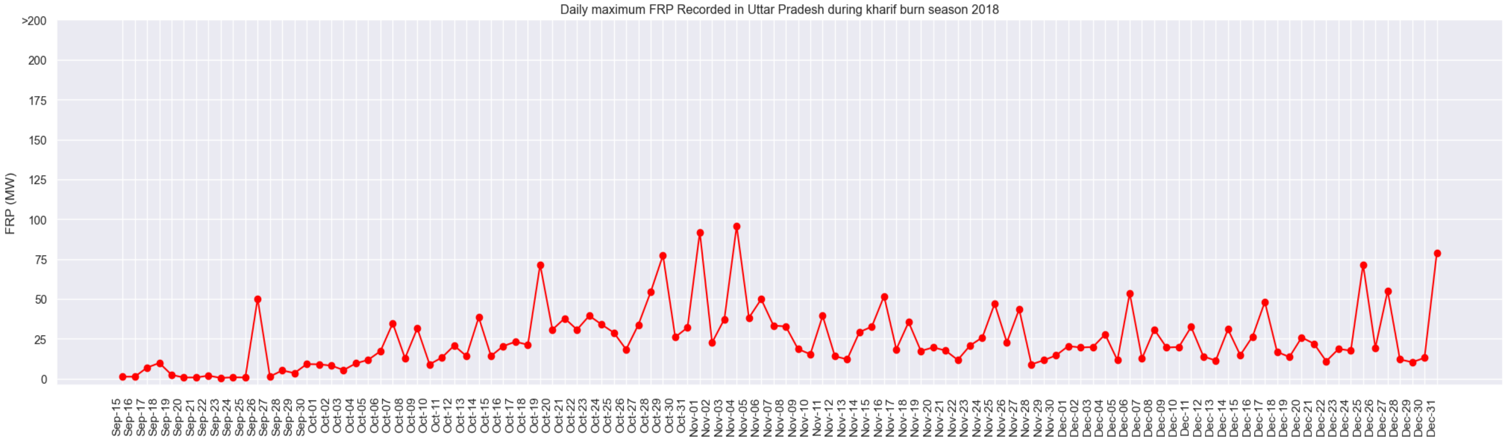


Fig 77: Daily maximum FRP in Uttar Pradesh from 15 September to 31 December in 2018

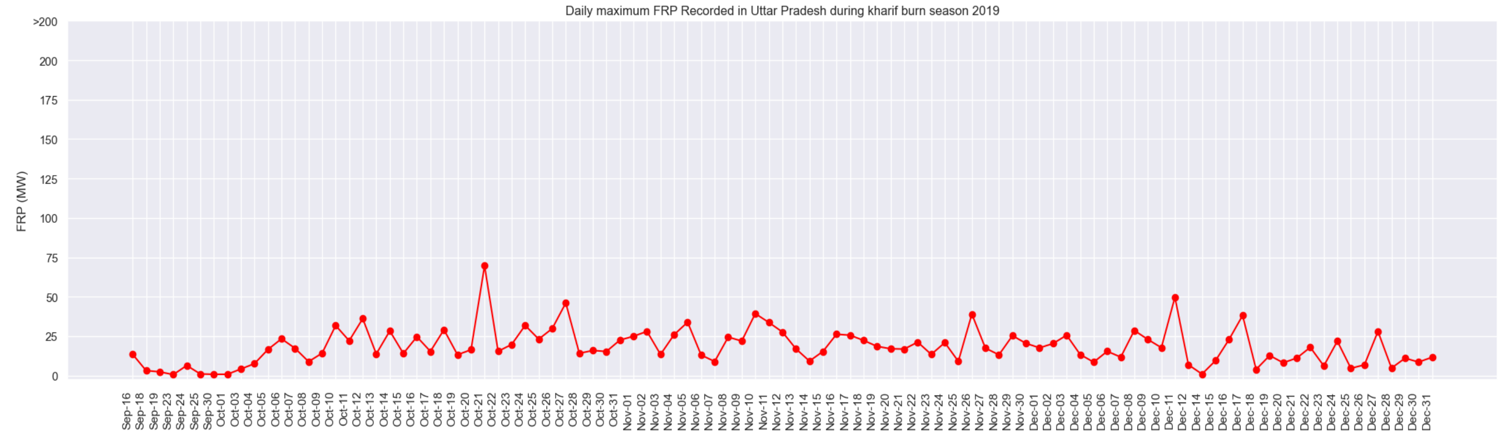


Fig 78: Daily maximum FRP in Uttar Pradesh from 15 September to 31 December in 2019

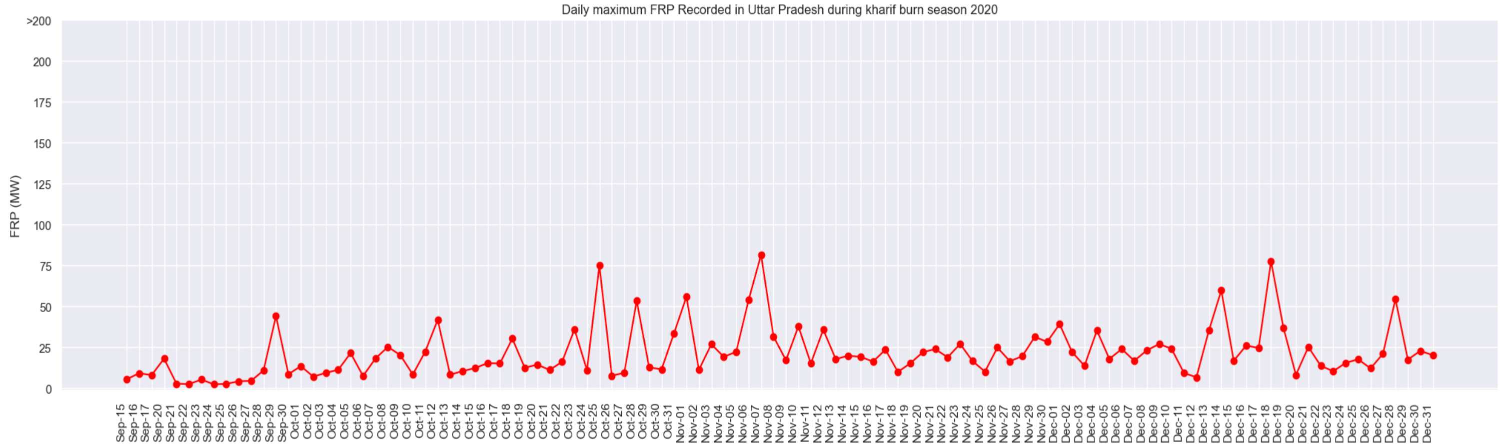


Fig 79: Daily maximum FRP in Uttar Pradesh from 15 September to 31 December in 2020

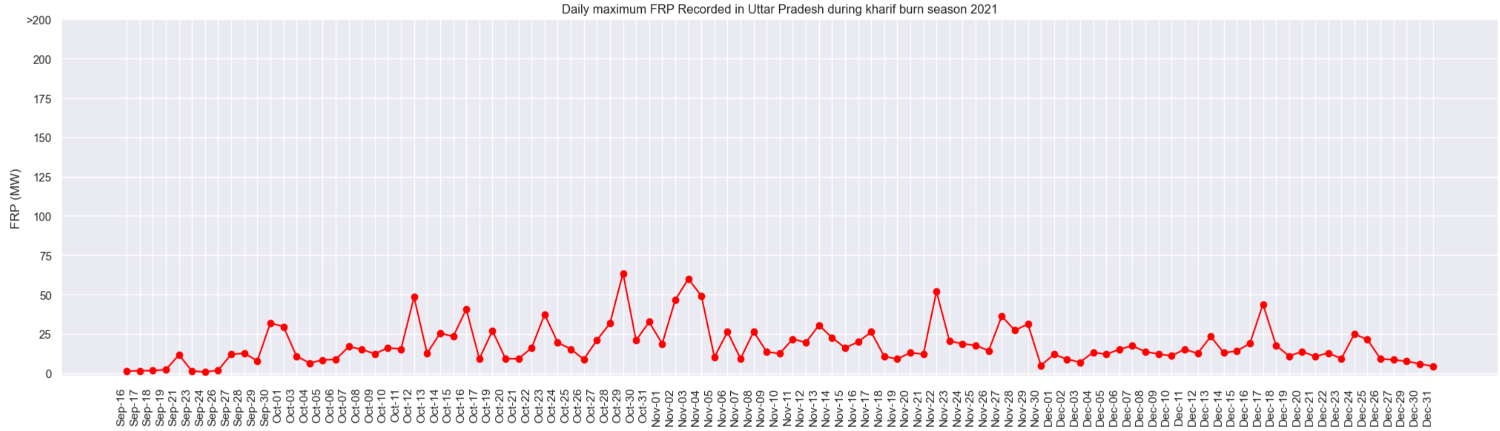


Fig 80: Daily maximum FRP in Uttar Pradesh from 15 September to 31 December in 2021

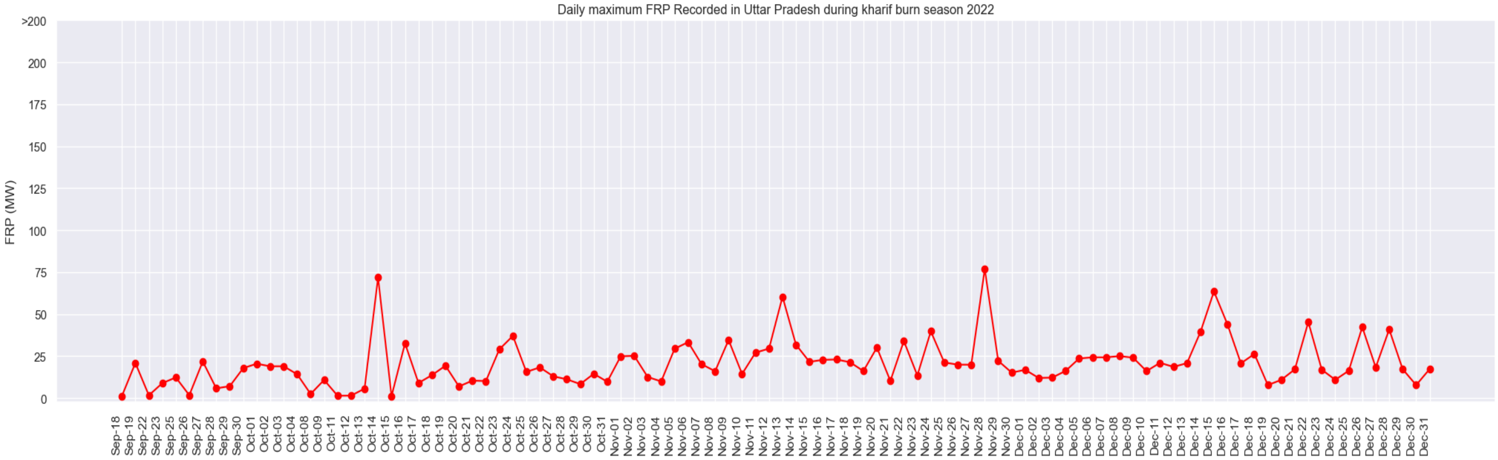


Fig 81: Daily maximum FRP in Uttar Pradesh from 15 September to 31 December in 2022

Figs 82 to Fig 87 represents the daily maximum FRP in Punjab from 15 March to 30 June (Rabi crop burning) for 2018-2023

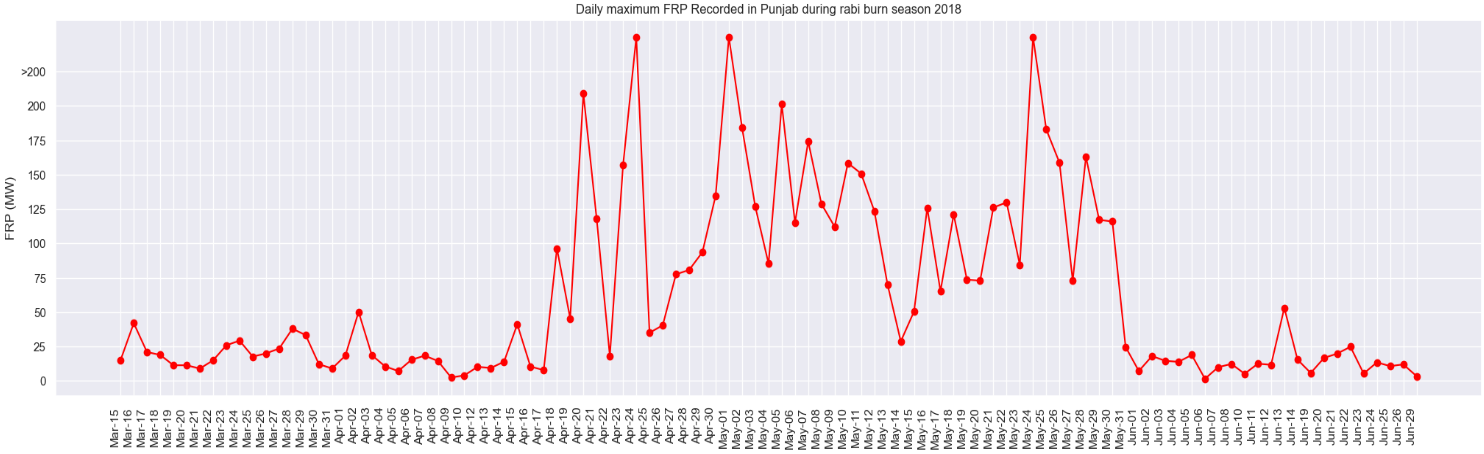


Fig 82: Daily maximum FRP in Punjab from 15 March to 30 June in 2018

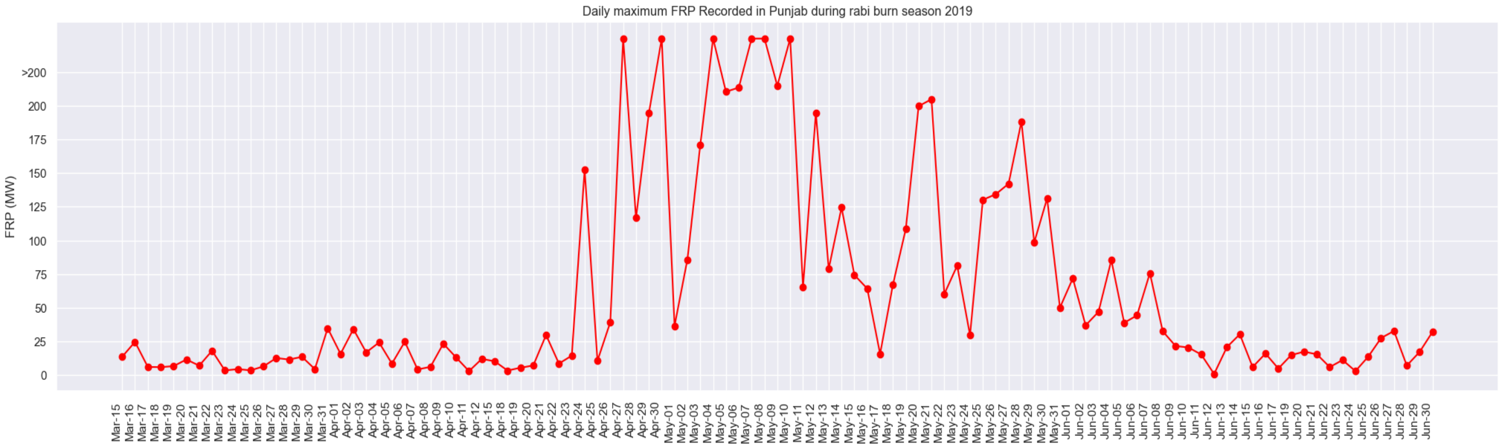


Fig 83: Daily maximum FRP in Punjab from 15 March to 30 June in 2019

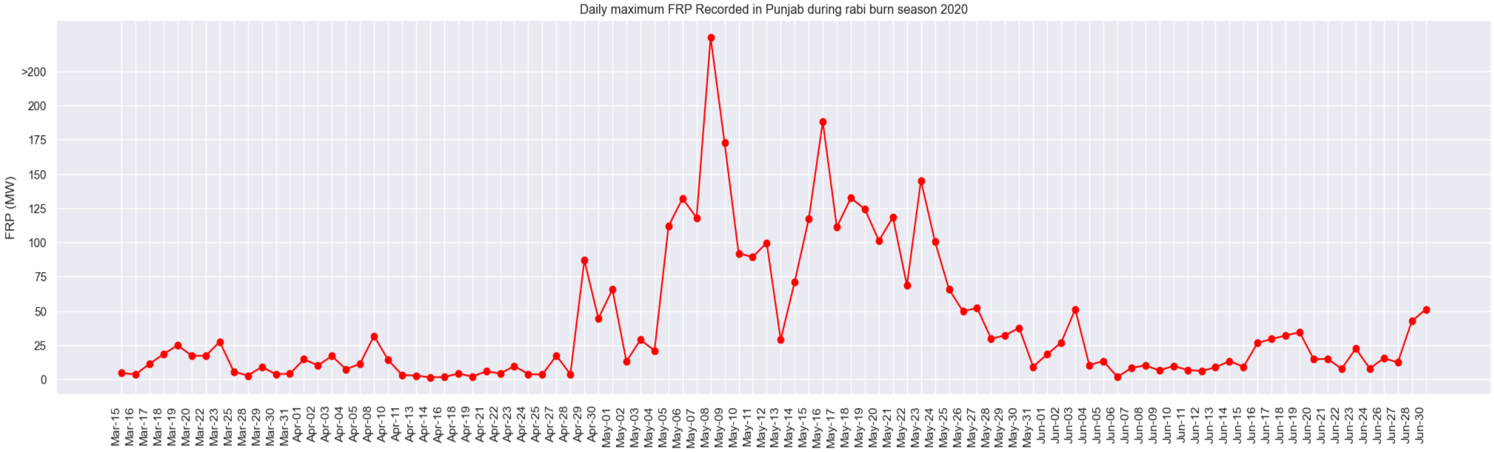


Fig 84: Daily maximum FRP in Punjab from 15 March to 30 June in 2020

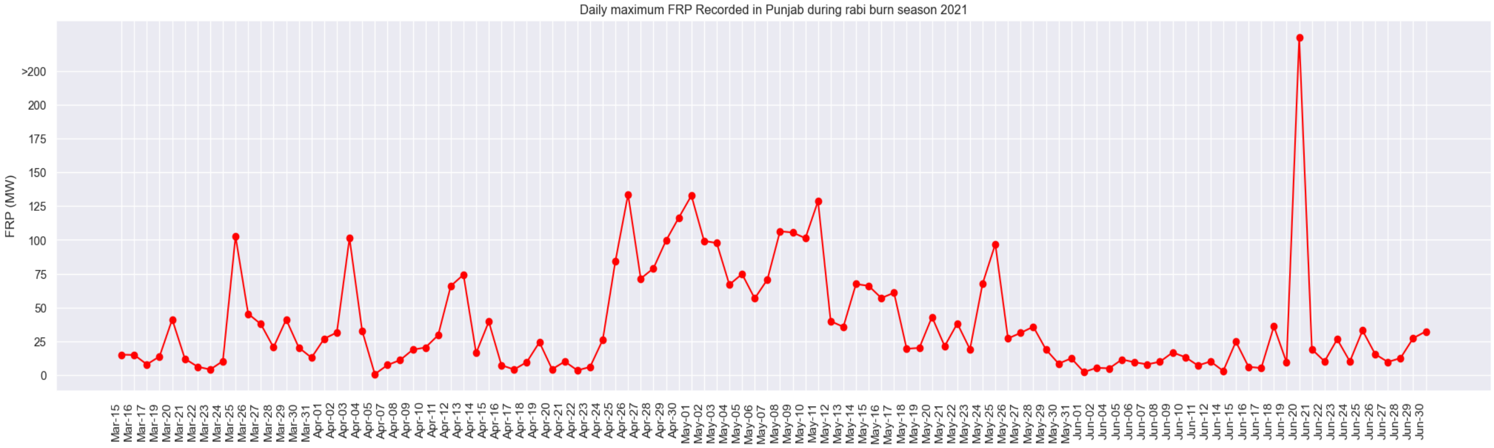


Fig 85: Daily maximum FRP in Punjab from 15 March to 30 June in 2021

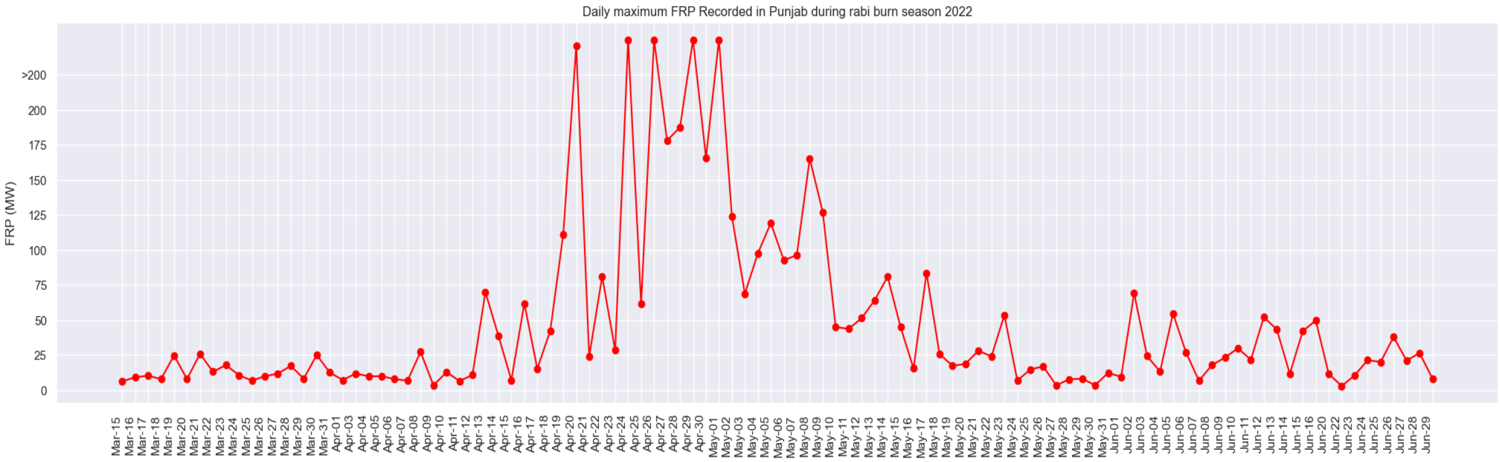


Fig 86: Daily maximum FRP in Punjab from 15 March to 30 June in 2022

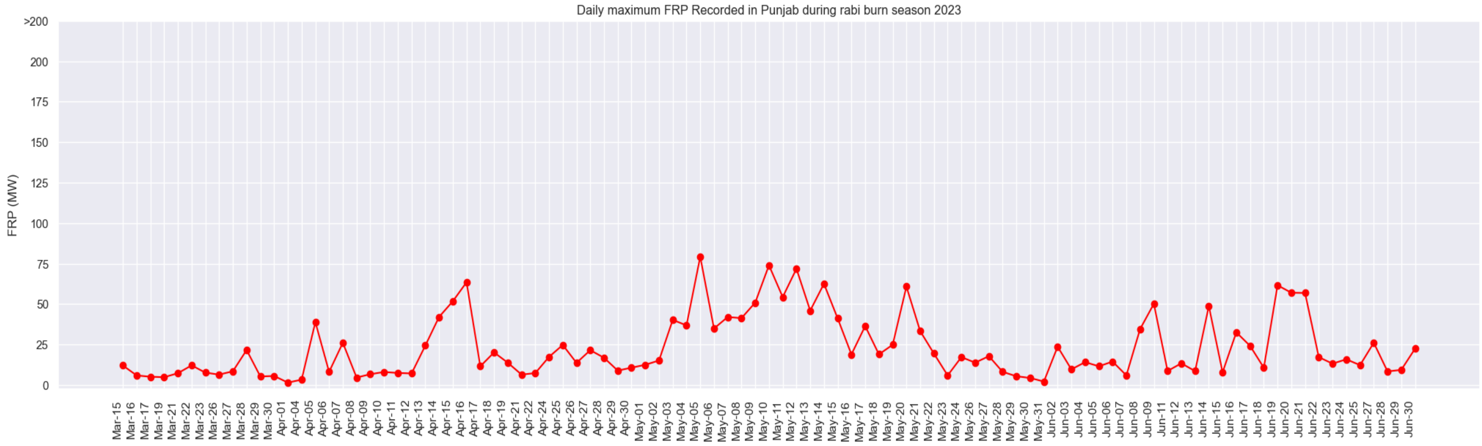


Fig 87: Daily maximum FRP in Punjab from 15 March to 30 June in 2023

Figs 88 to Fig 93 represents the daily maximum FRP in Haryana from 15 March to 30 June (Rabi crop burning) for 2018-2023

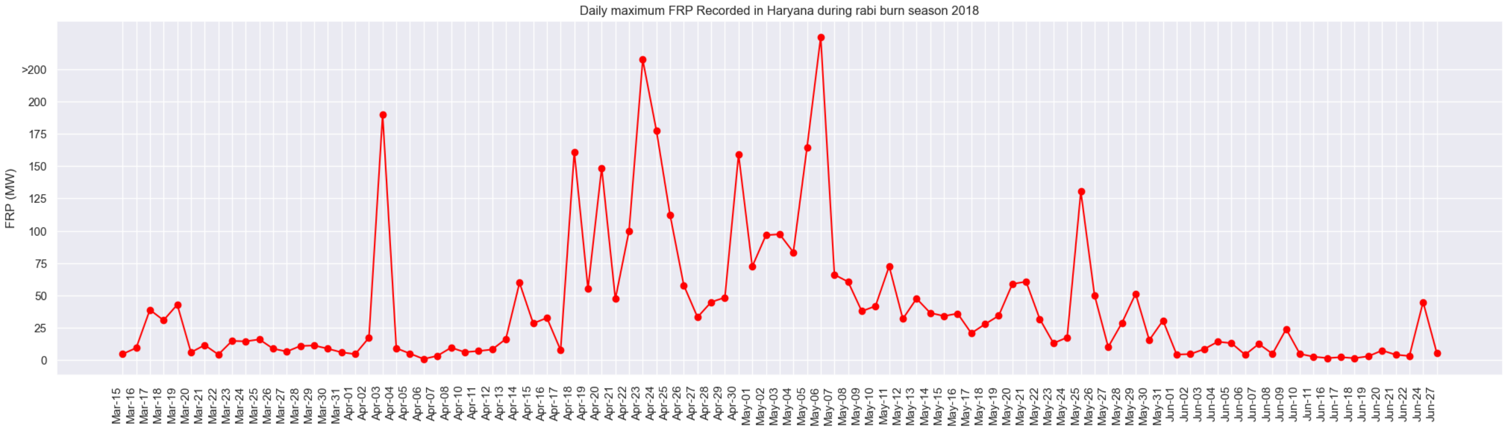


Fig 88: Daily maximum FRP in Haryana from 15 March to 30 June in 2018

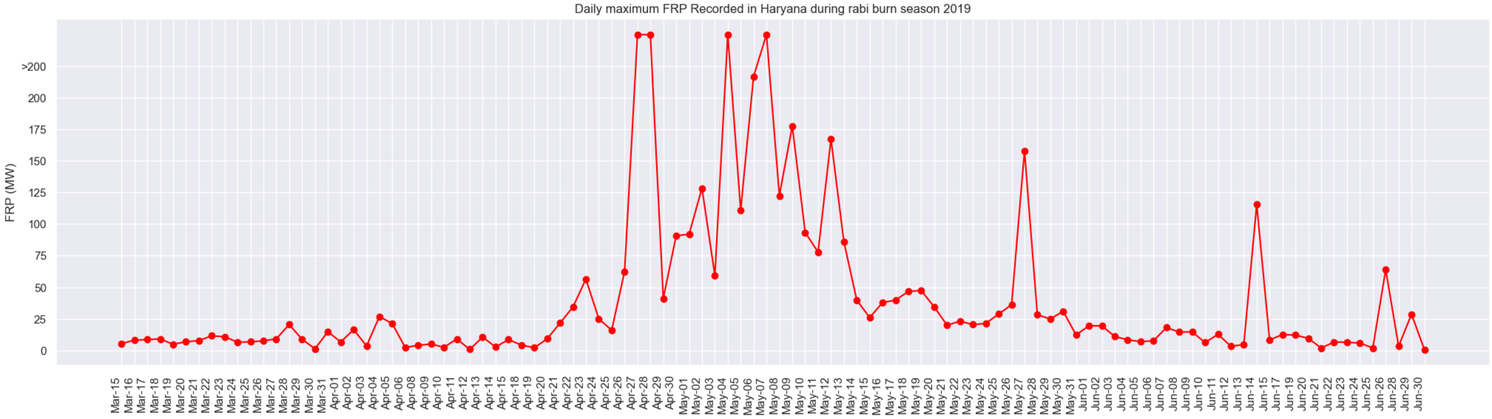


Fig 89: Daily maximum FRP in Haryana from 15 March to 30 June in 2019

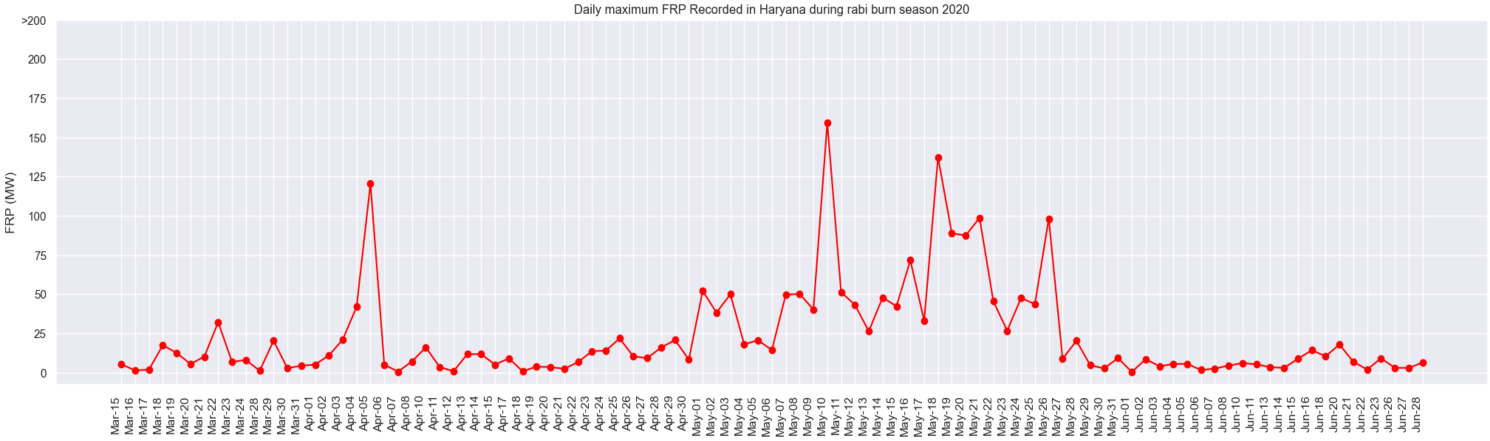


Fig 90: Daily maximum FRP in Haryana from 15 March to 30 June in 2020

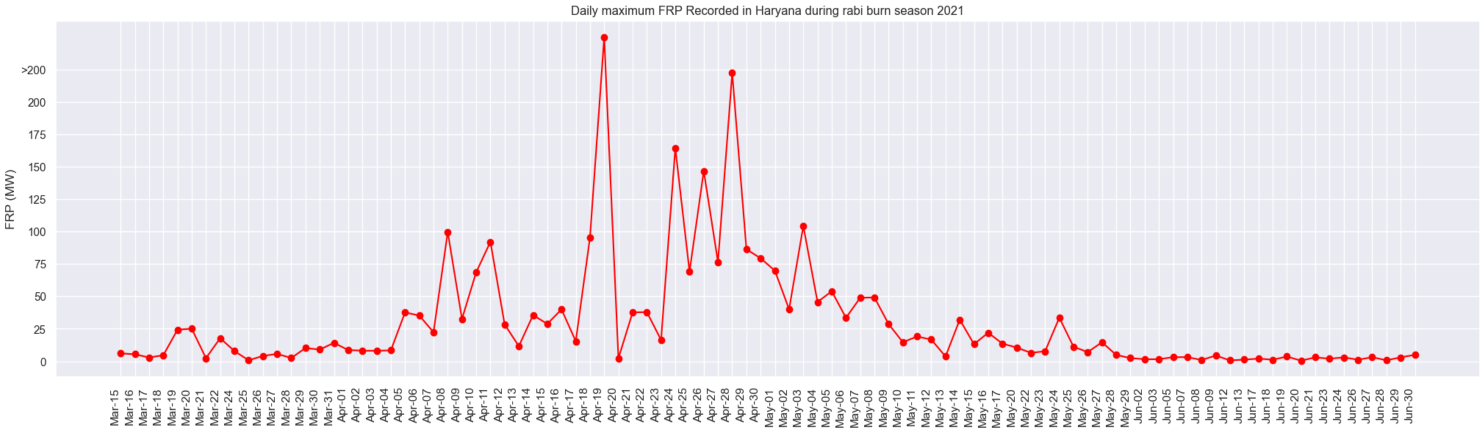


Fig 91: Daily maximum FRP in Haryana from 15 March to 30 June in 2021

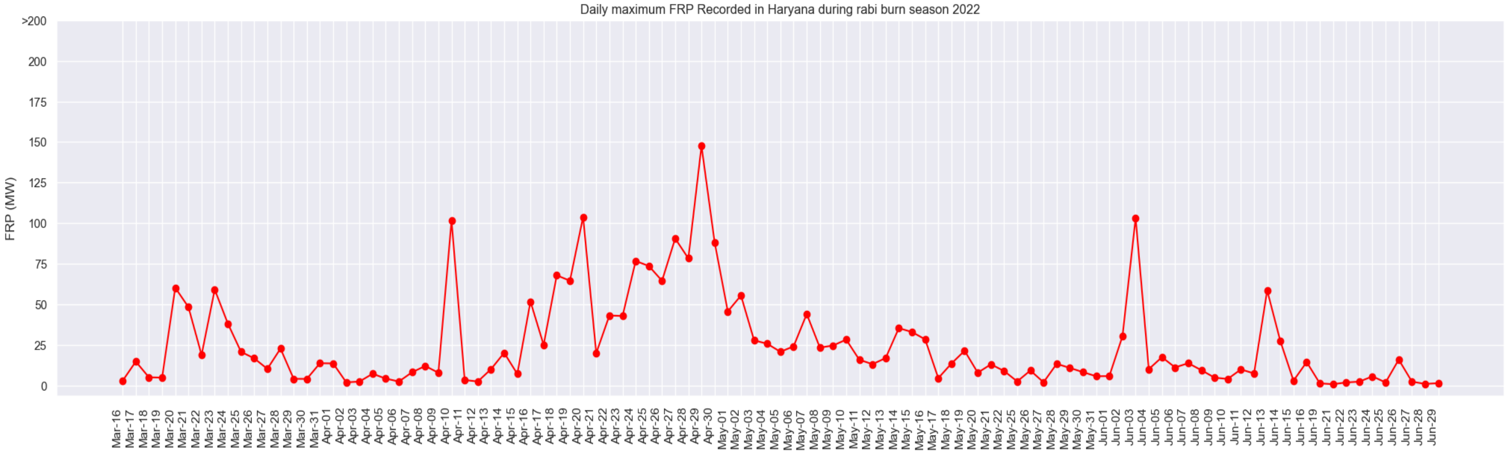


Fig 92: Daily maximum FRP in Haryana from 15 March to 30 June in 2022

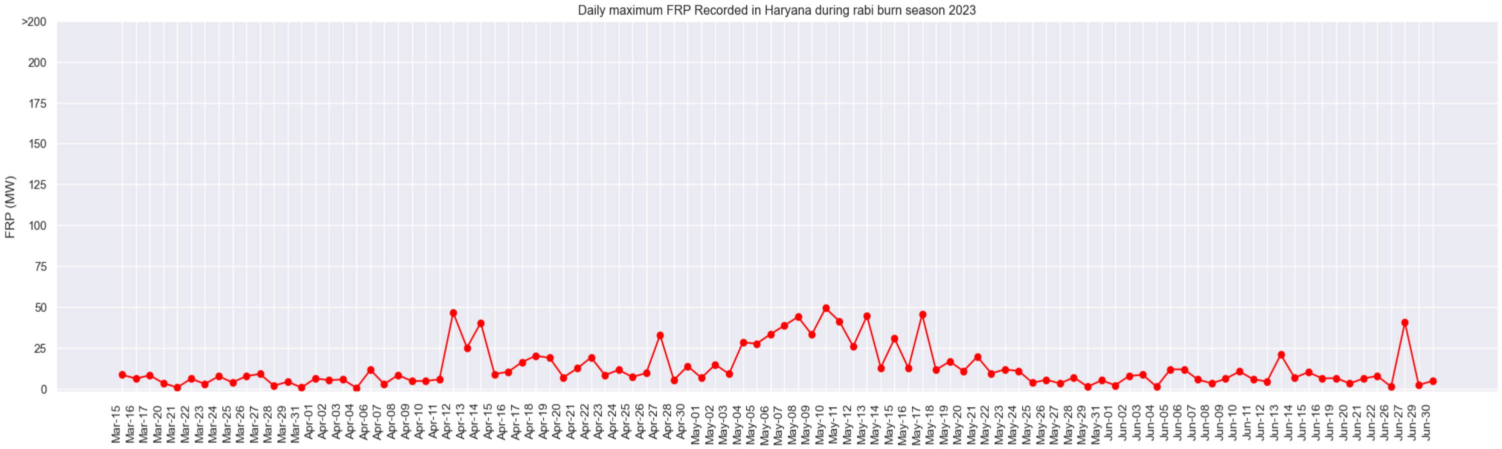


Fig 93: Daily maximum FRP in Haryana from 15 March to 30 June in 2023

Figs 94 to Fig 99 represents the daily maximum FRP in Uttar Pradesh from 15 March to 30 June (Rabi crop burning) for 2018-2023

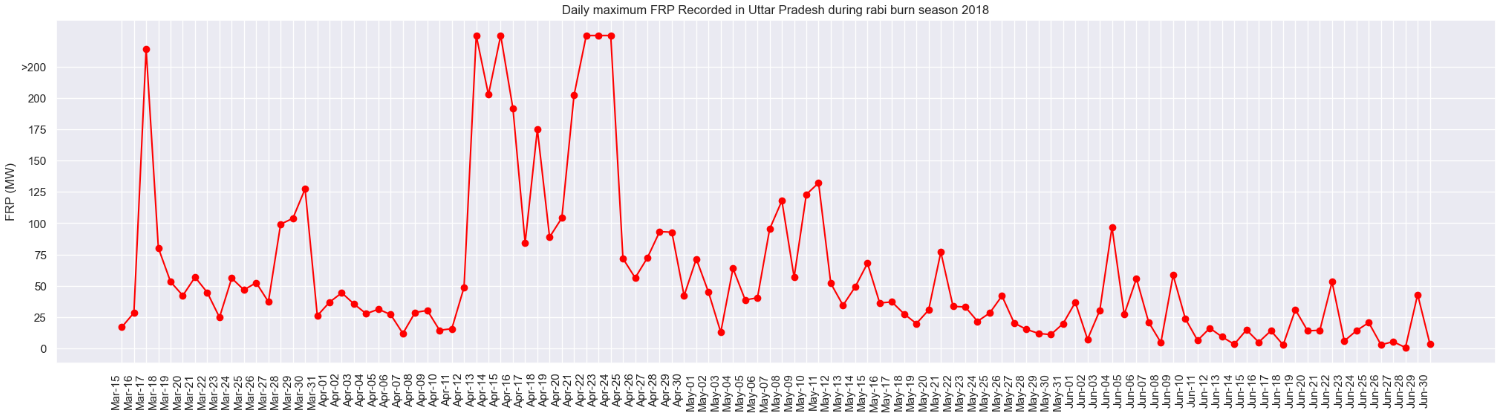


Fig 94: Daily maximum FRP in Uttar Pradesh from 15 March to 30 June in 2018

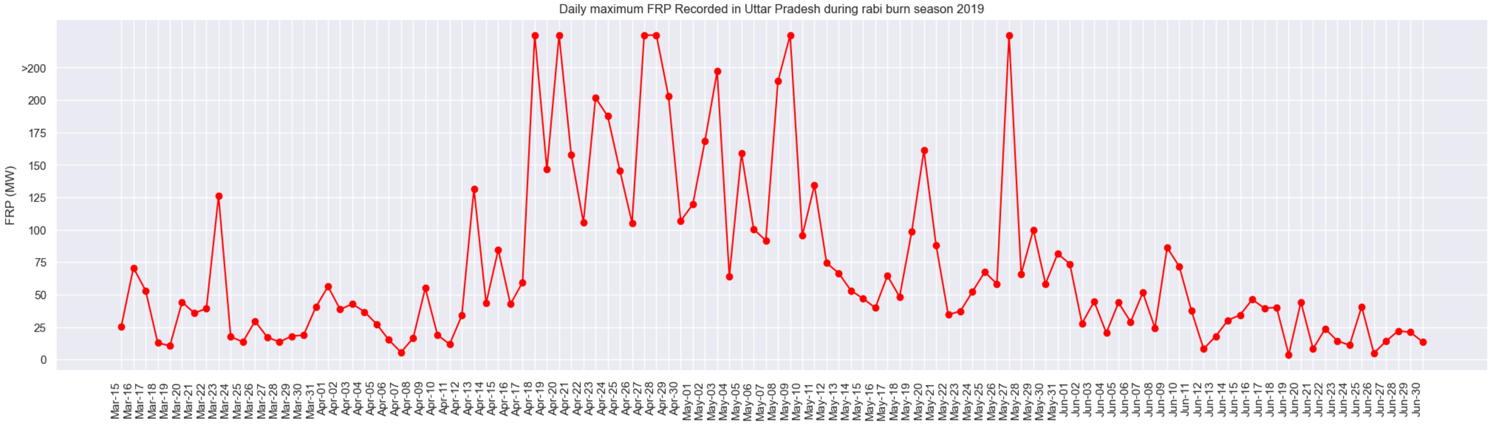


Fig 95: Daily maximum FRP in Uttar Pradesh from 15 March to 30 June in 2019

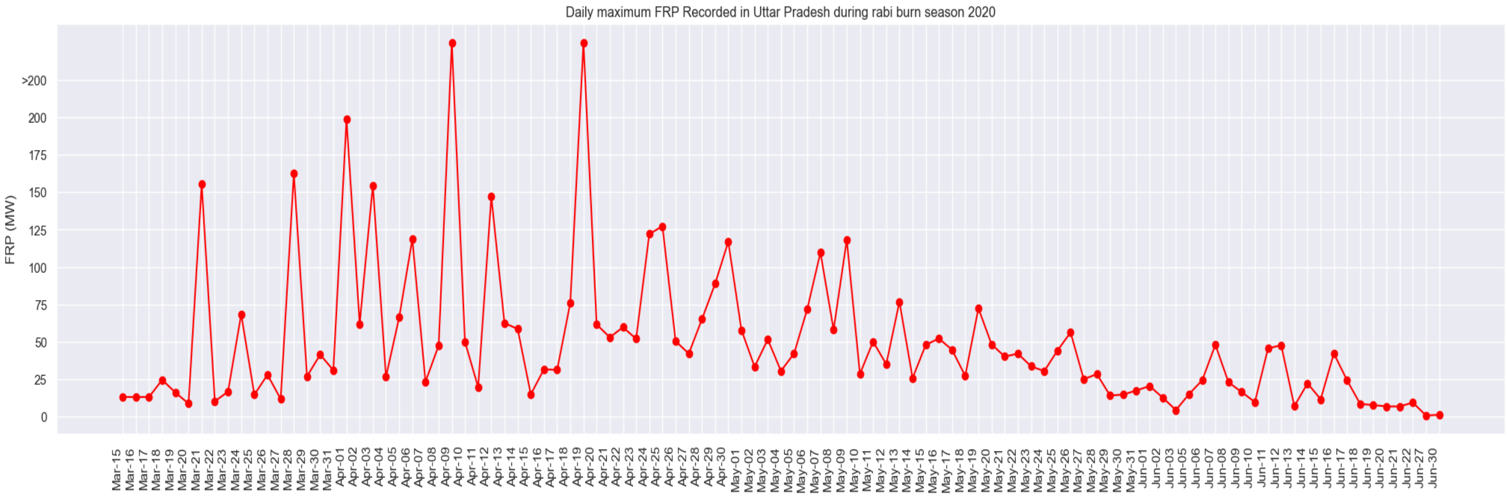


Fig 96: Daily maximum FRP in Uttar Pradesh from 15 March to 30 June in 2020

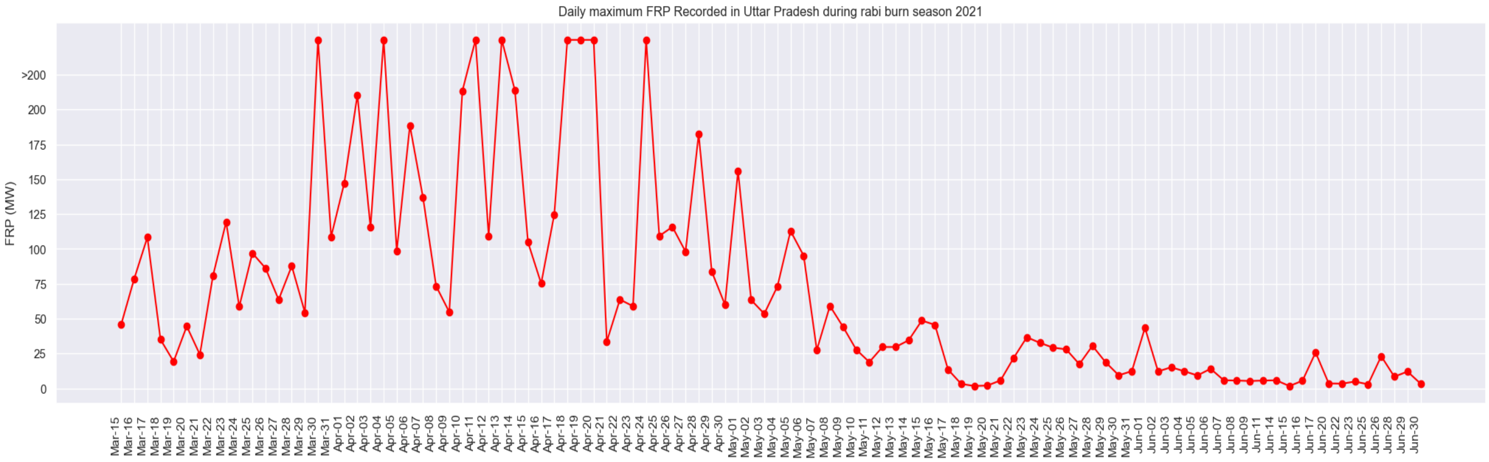


Fig 97: Daily maximum FRP in Uttar Pradesh from 15 March to 30 June in 2021

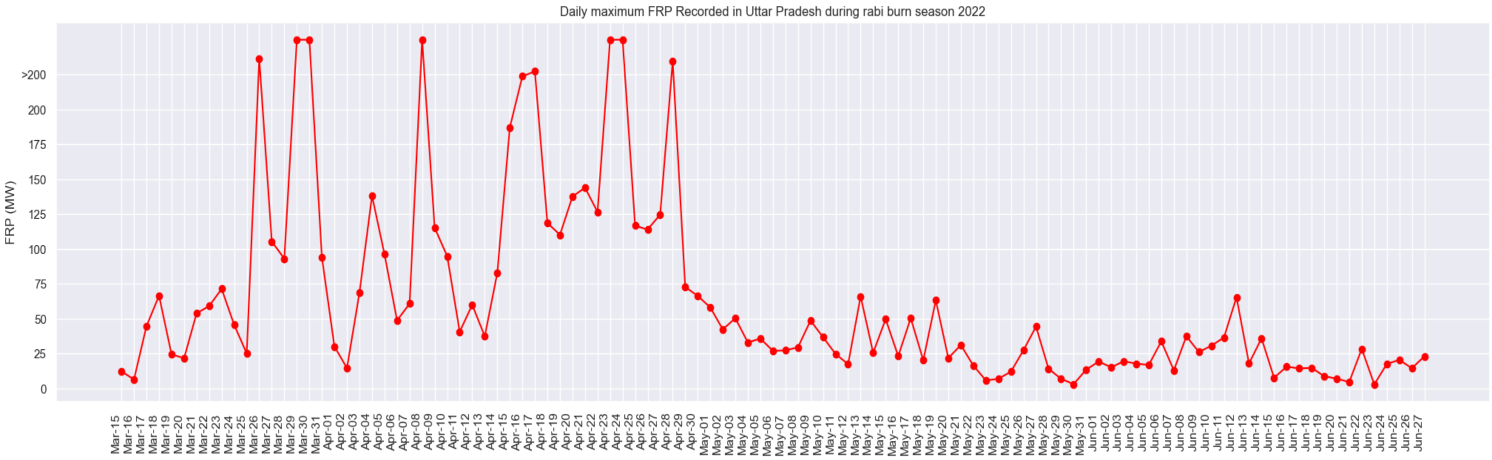


Fig 98: Daily maximum FRP in Uttar Pradesh from 15 March to 30 June in 2022

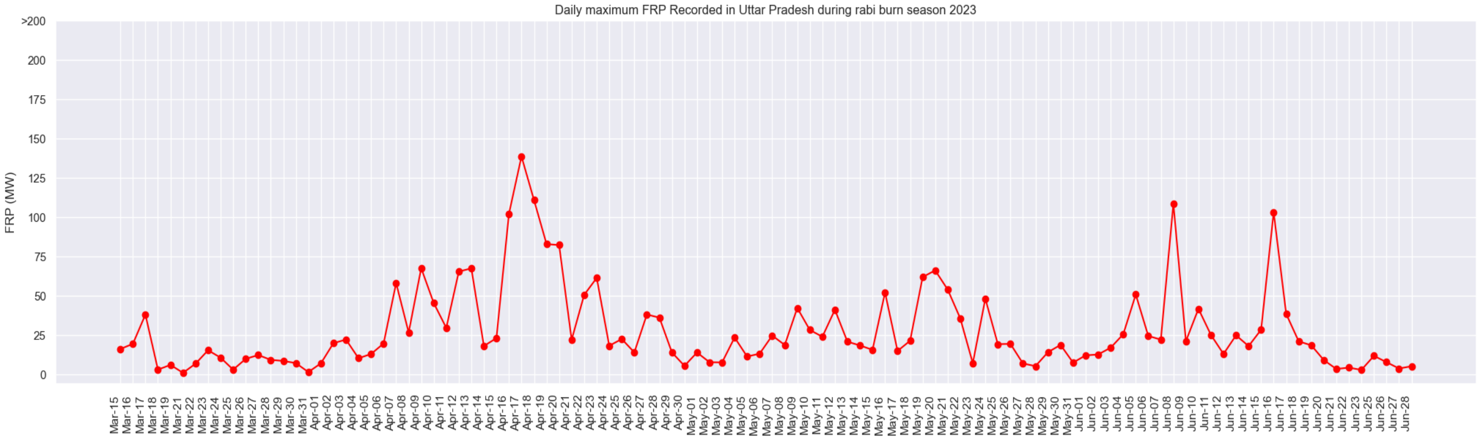


Fig 99: Daily maximum FRP in Uttar Pradesh from 15 March to 30 June in 2023

Subsequently, our analysis focused on examining the daily maximum Fire Radiative Power (FRP) plot alongside the daily maximum PM2.5 plot. This approach aimed to identify any potential patterns or dependencies between these two variables.

Figs 100 to Fig 104 shows the combined plot of FRP and PM2.5 concentration during the kharif crop burning in Punjab from 2018 to 2022

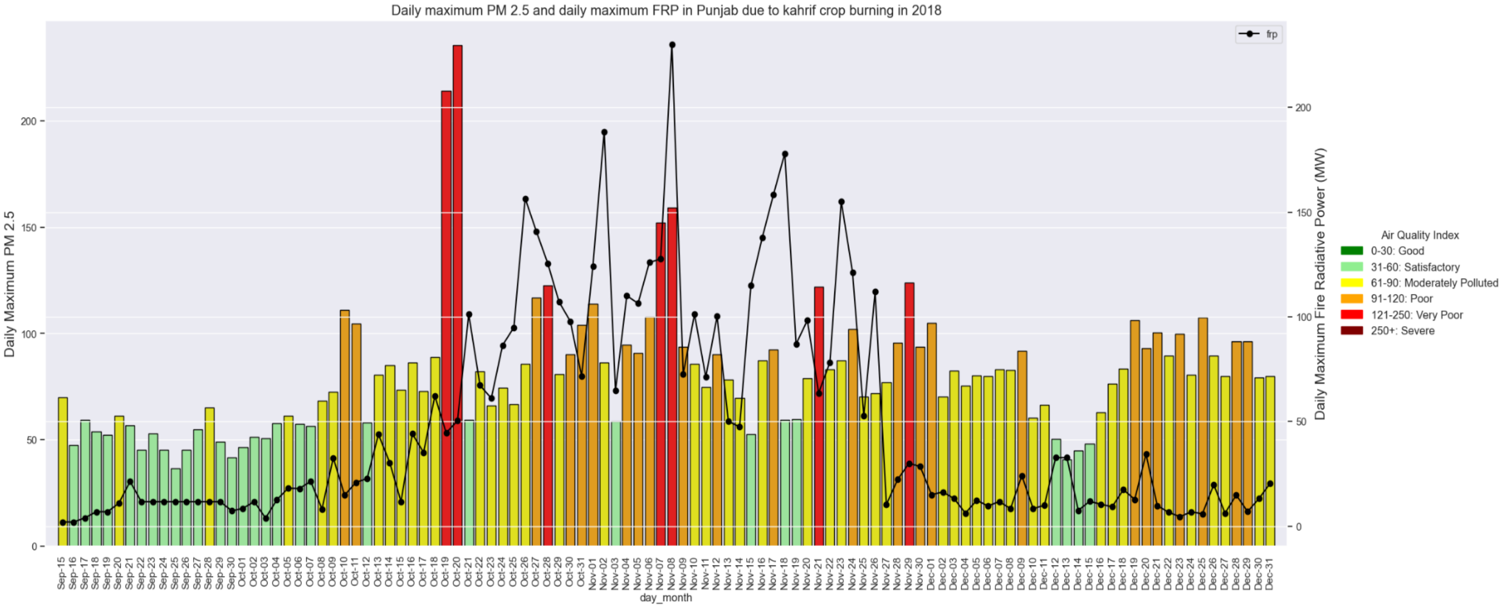


Fig 100: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2018

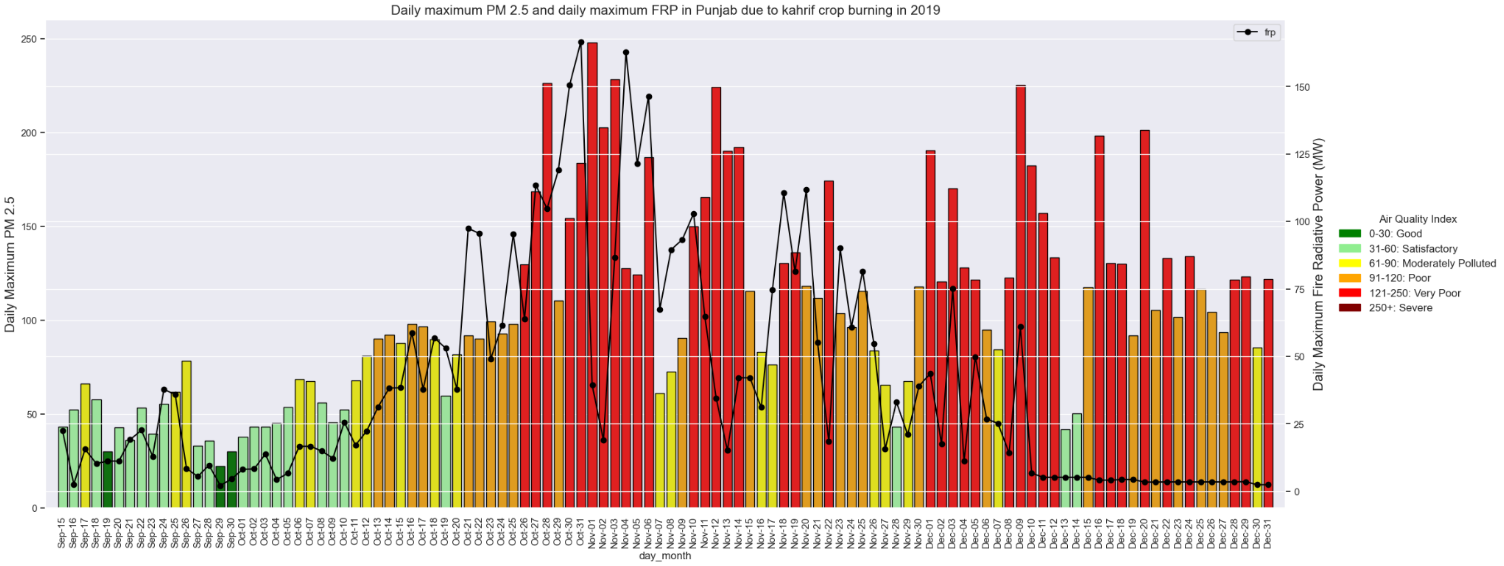


Fig 101: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2019

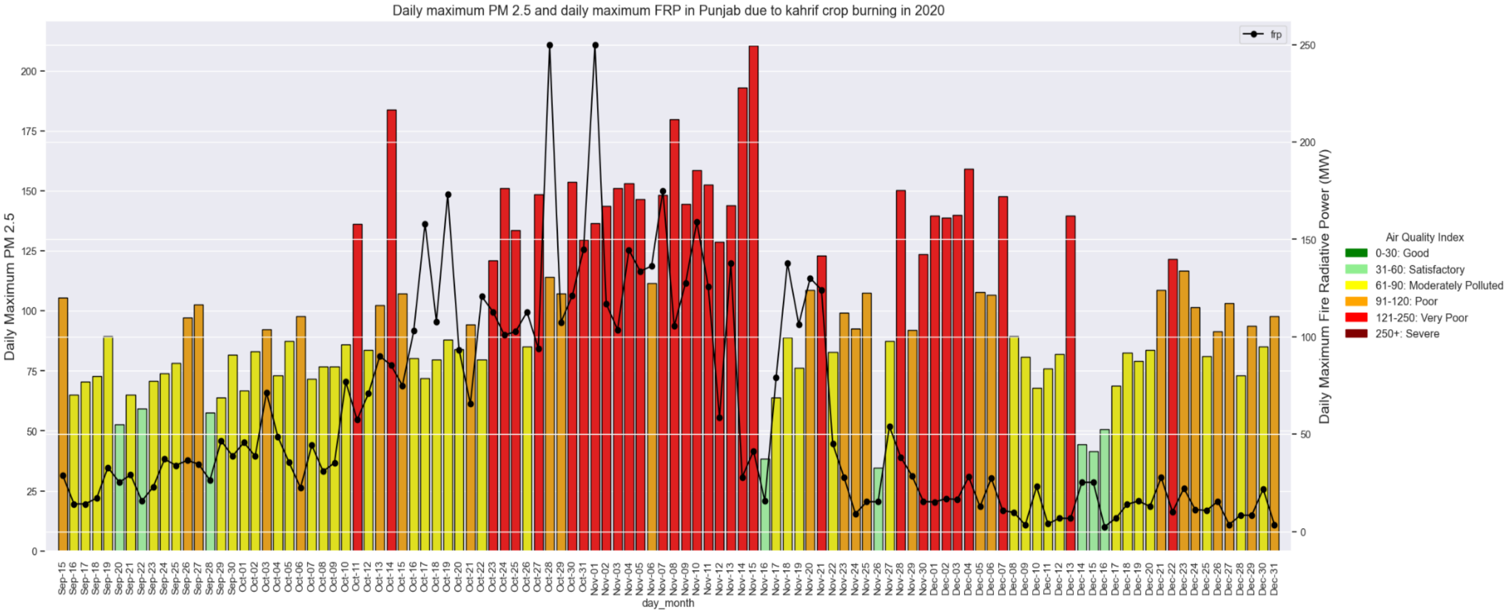


Fig 102: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2020

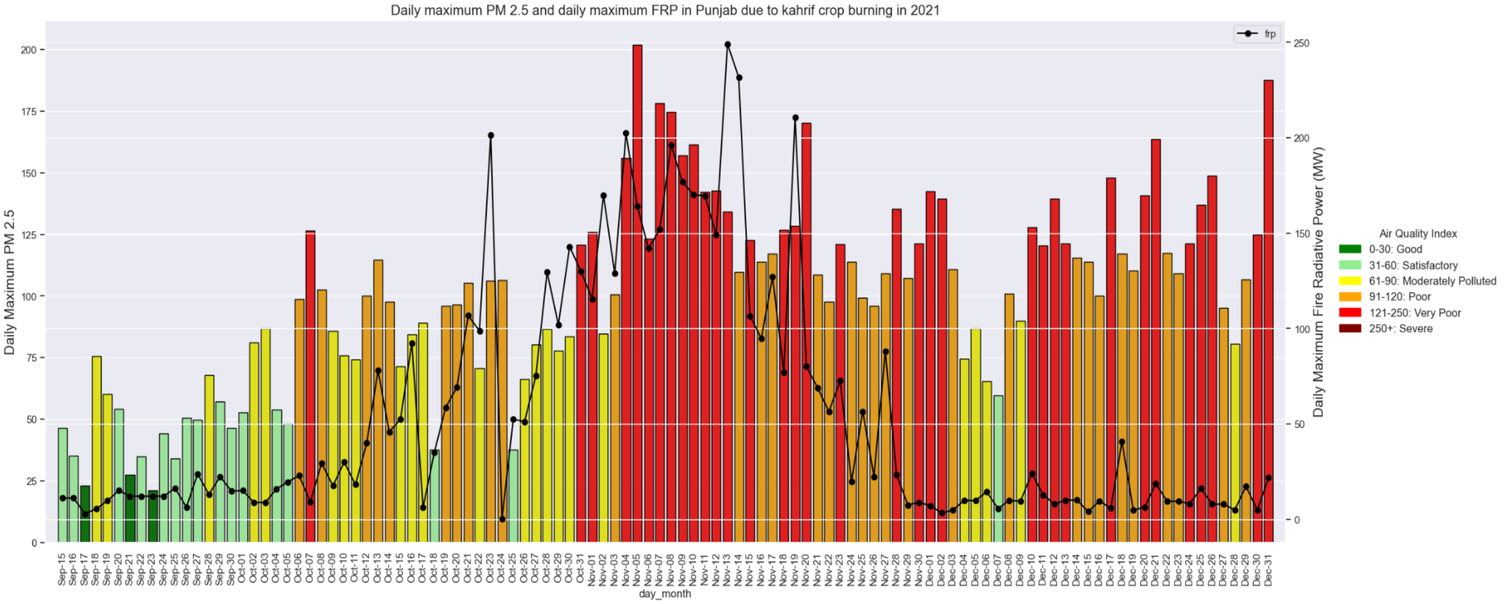


Fig 103: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2021

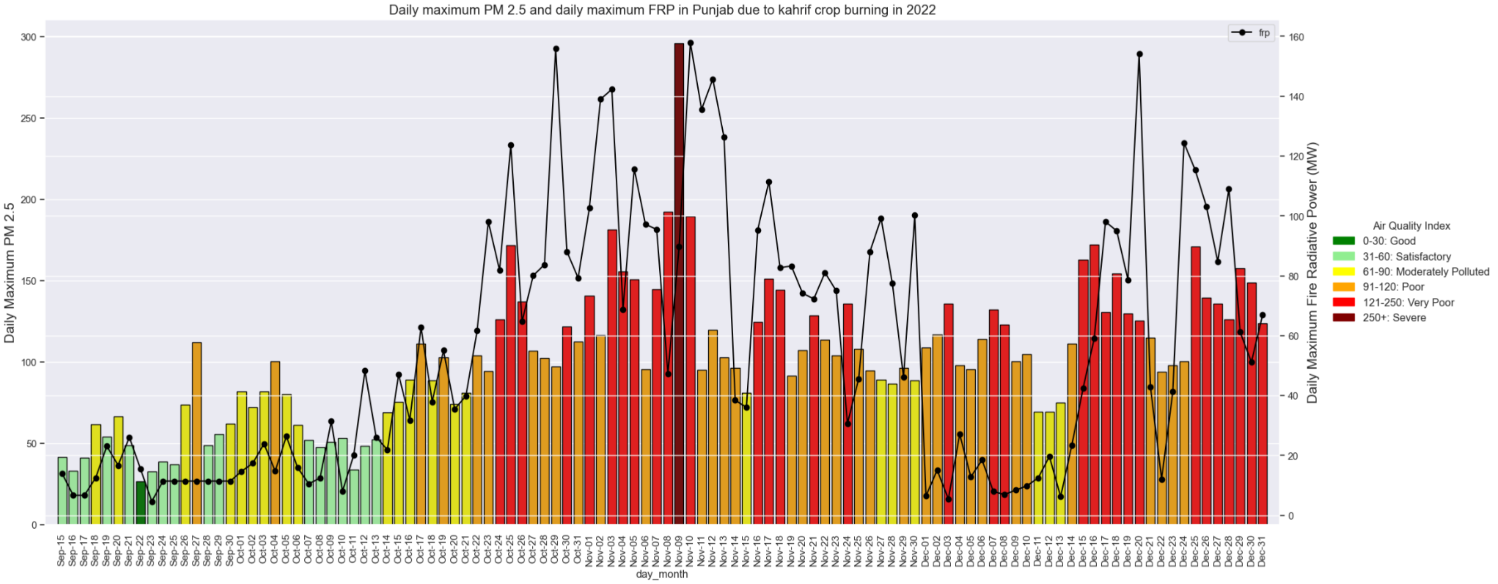


Fig 104: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2022

Figs 105 to Fig 109 shows the combined plot of FRP and PM2.5 concentration during the kharif crop burning in Haryana from 2018 to 2022

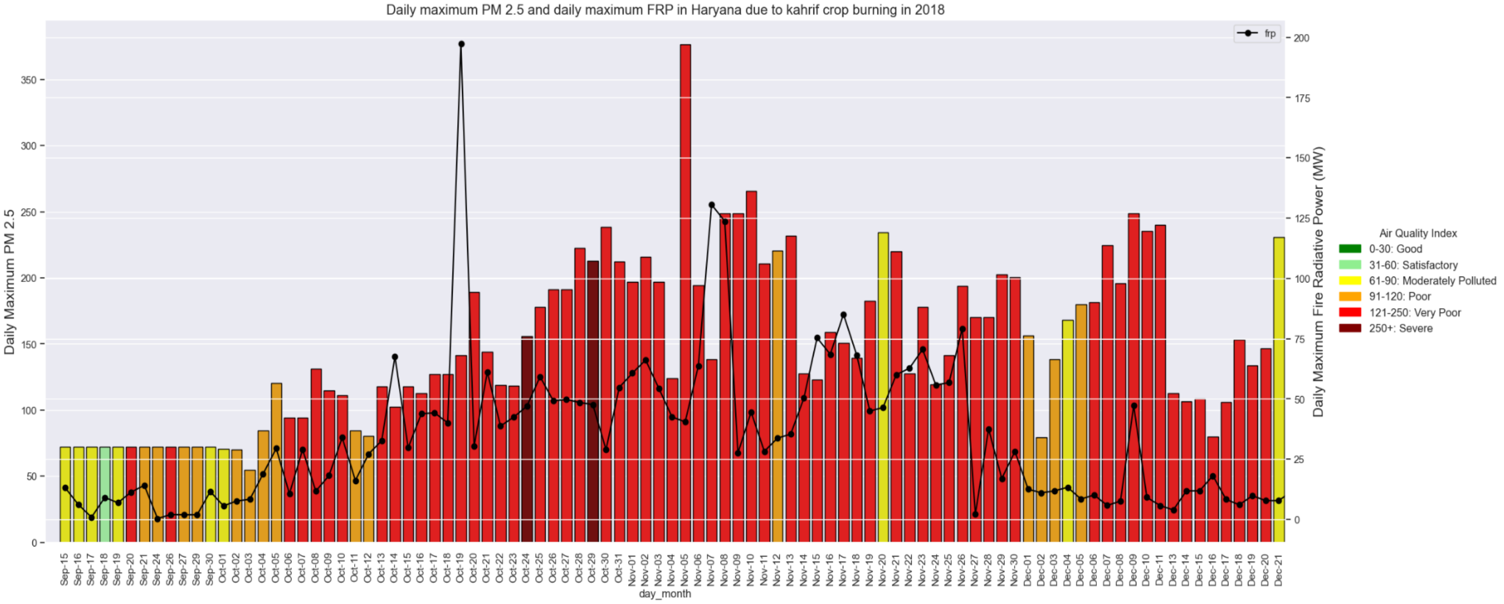


Fig 105: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2018

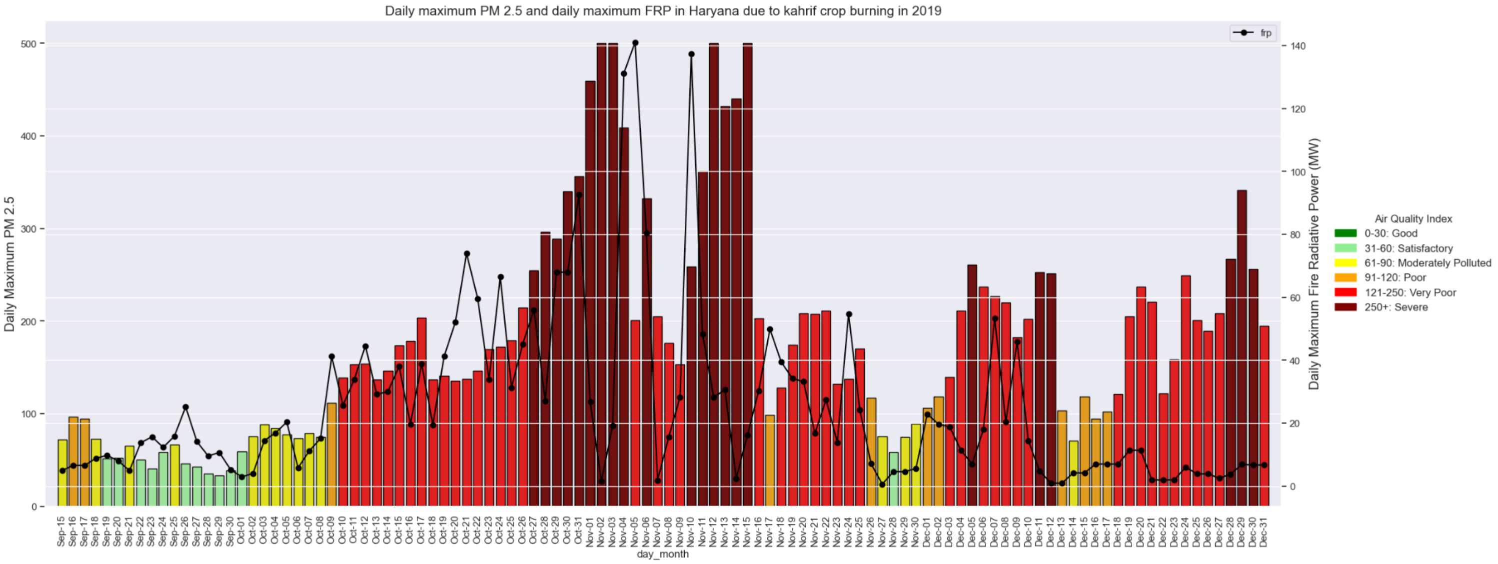


Fig 106: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2019

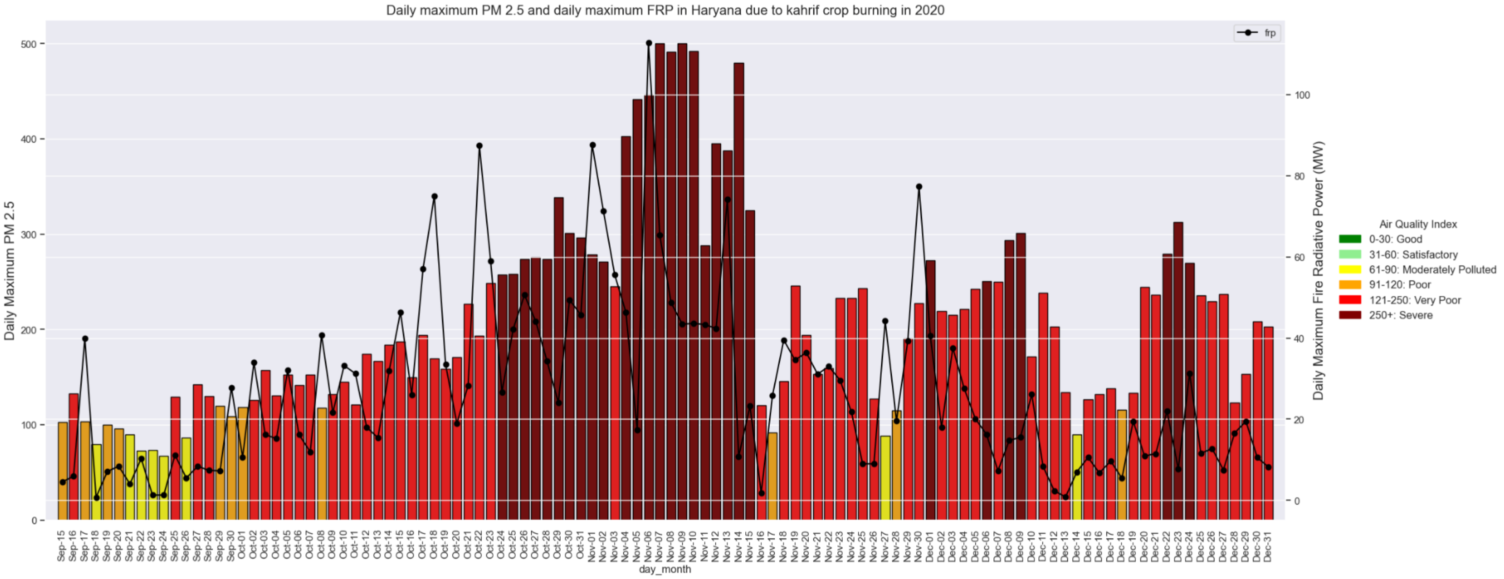


Fig 107: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2020

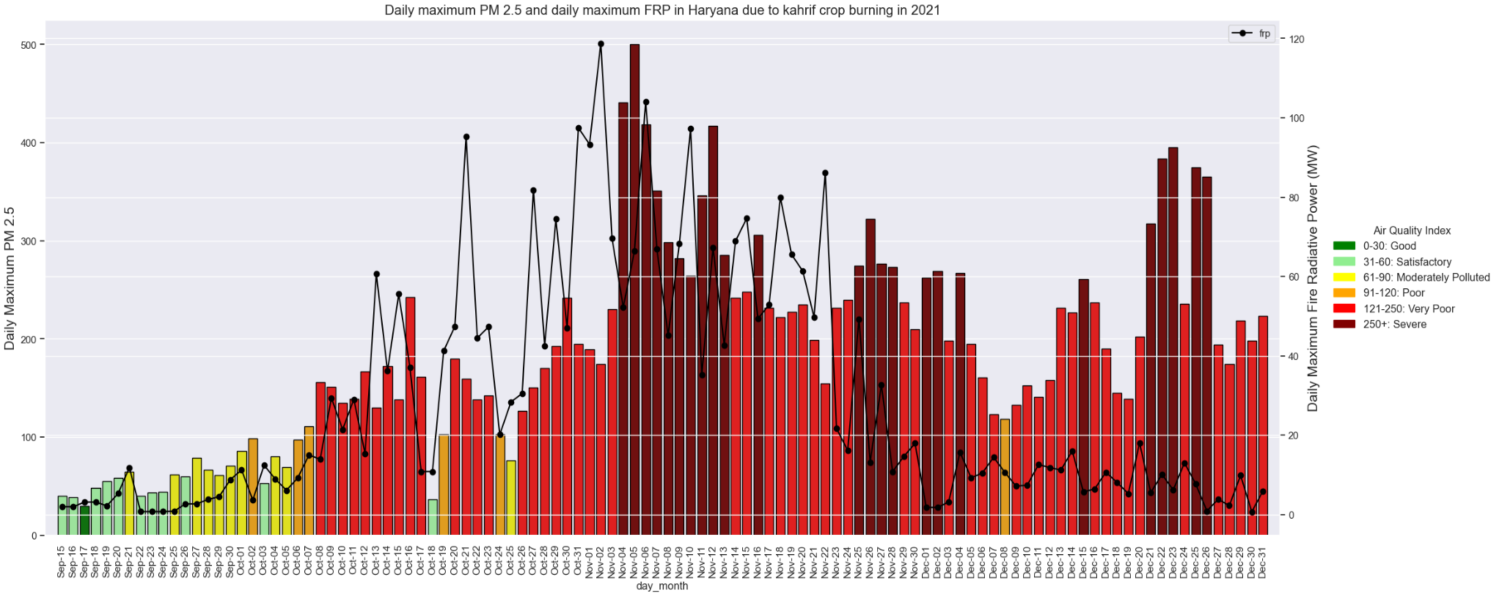


Fig 108: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2021

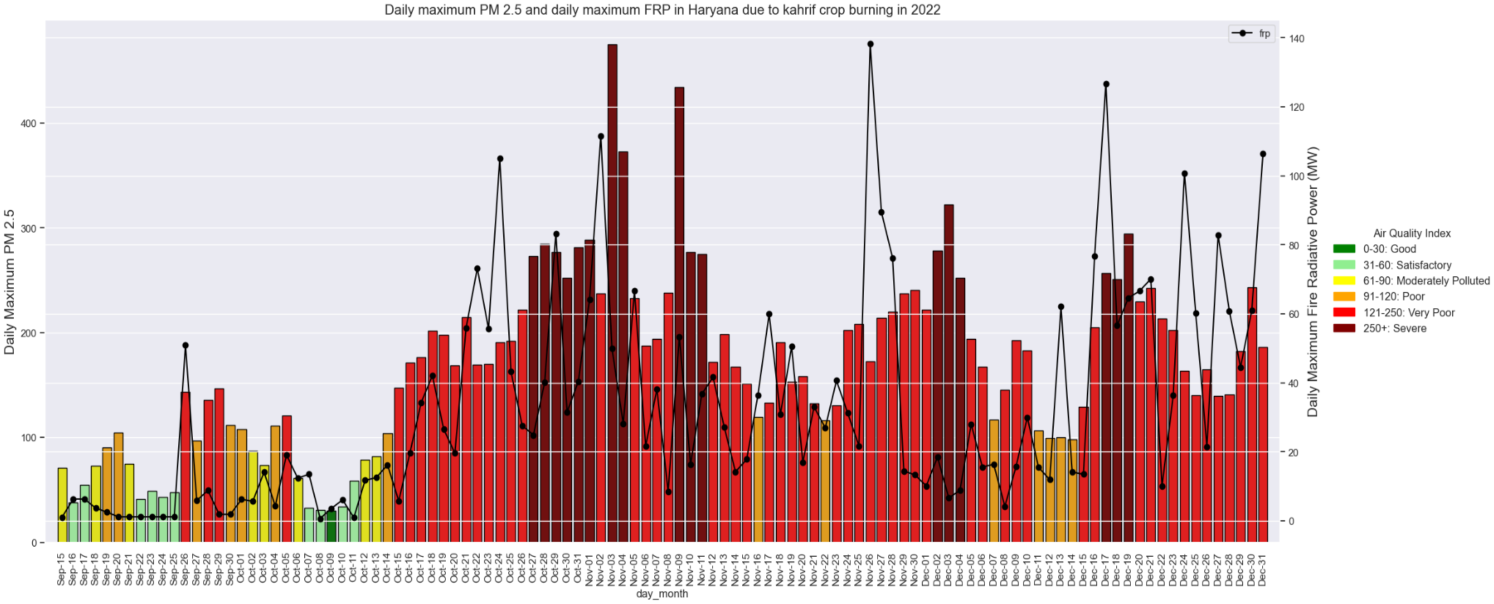


Fig 109: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2022

Figs 110 to Fig 114 shows the combined plot of FRP and PM2.5 concentration during the kharif crop burning in Uttar Pradesh from 2018 to 2022

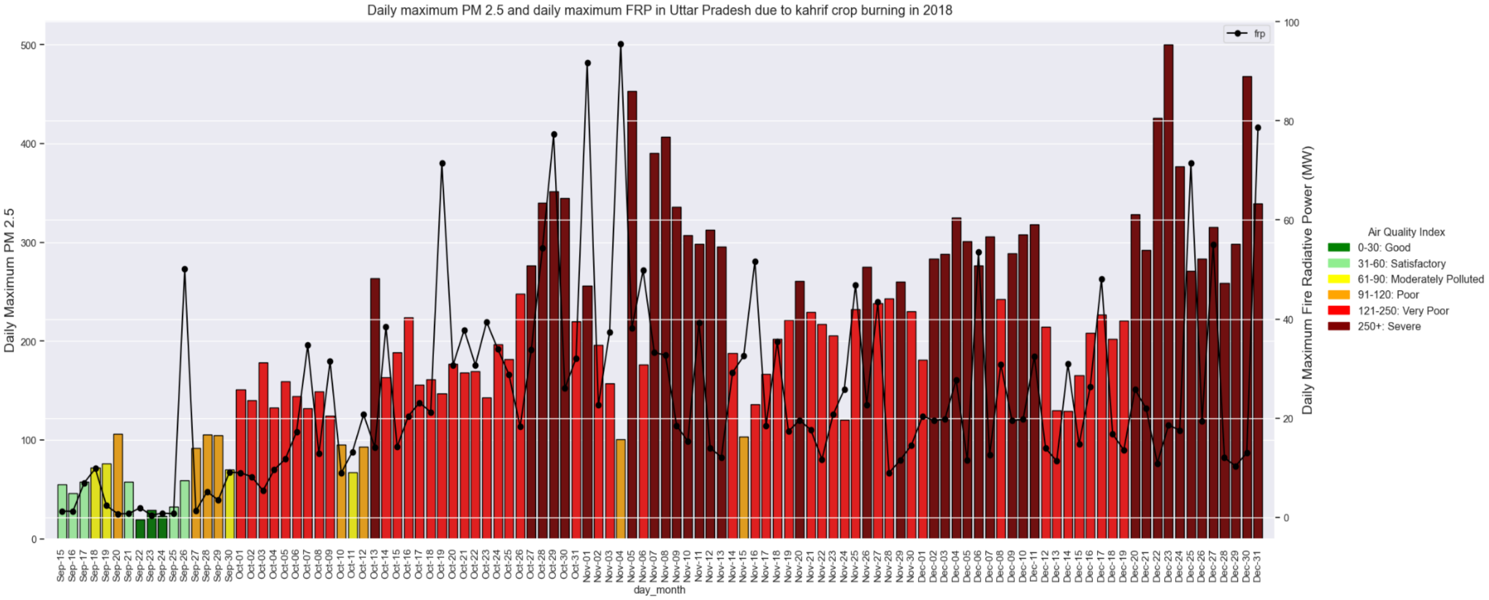


Fig 110: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2018

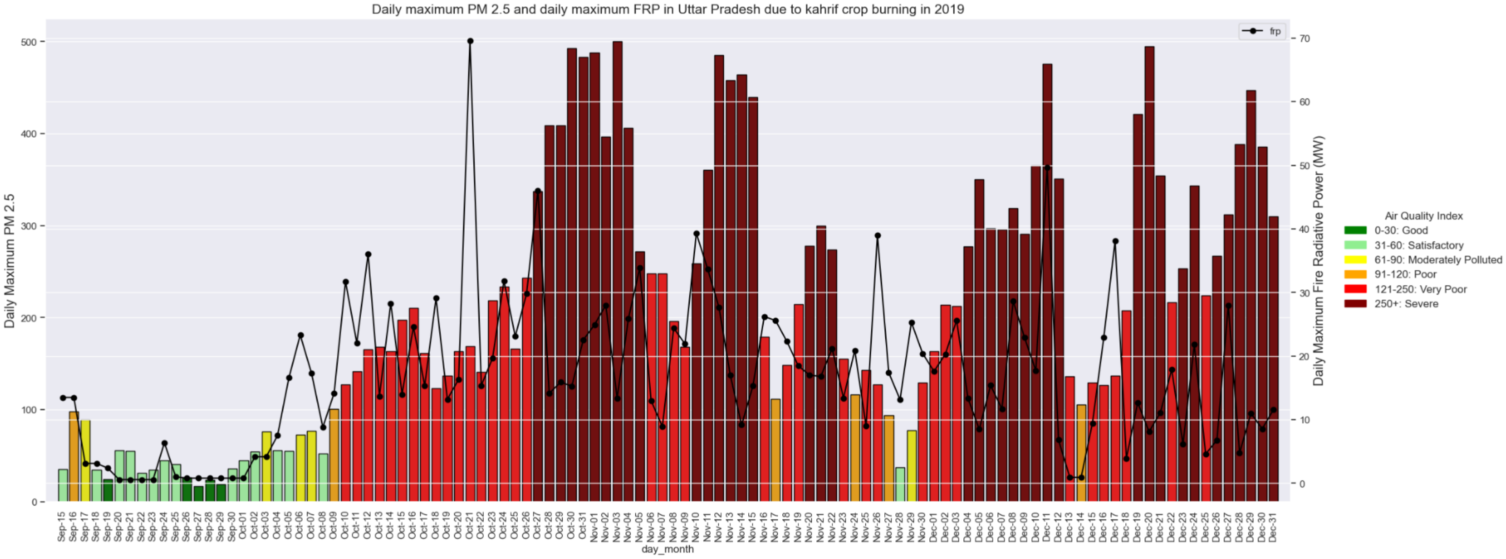


Fig 119: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2019

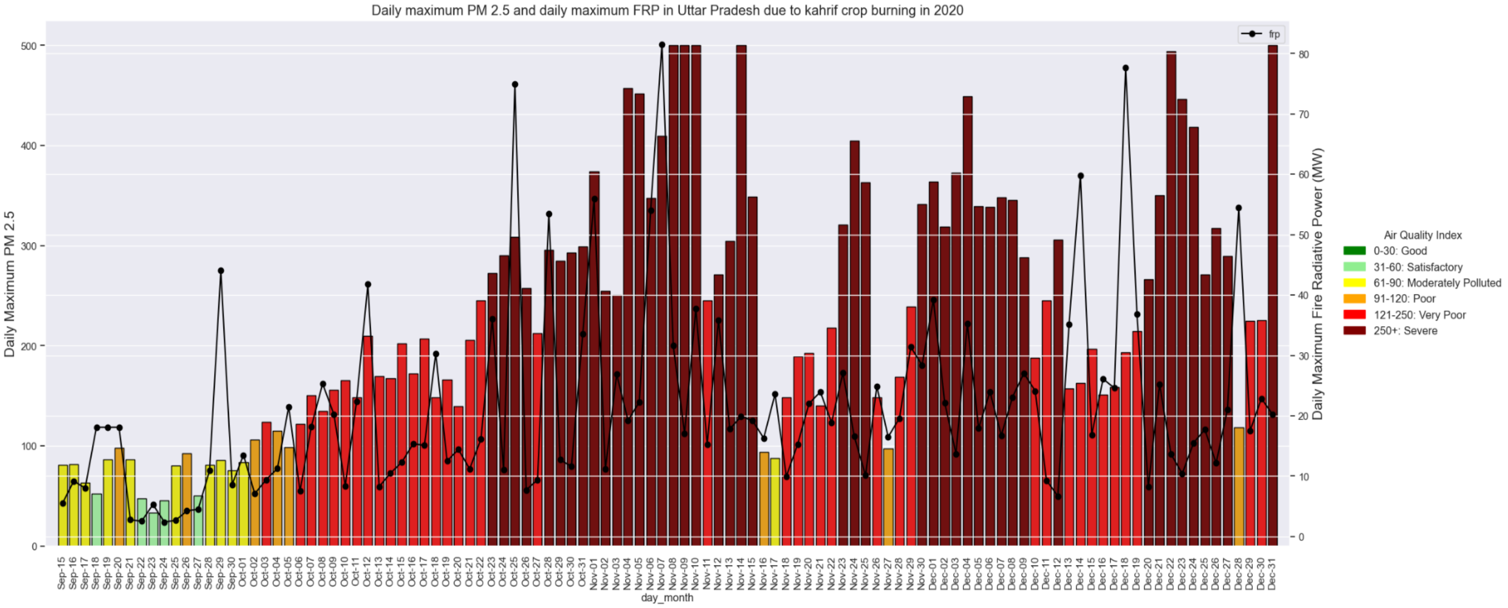


Fig 120: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2020

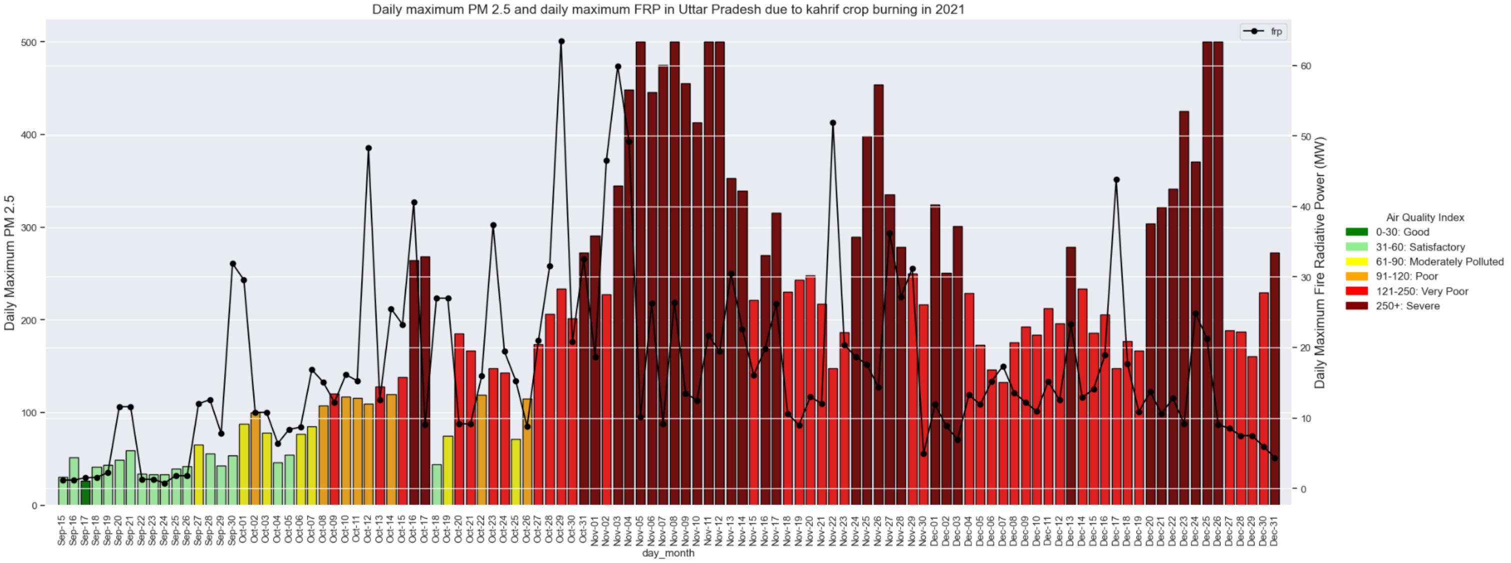


Fig 121: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2021

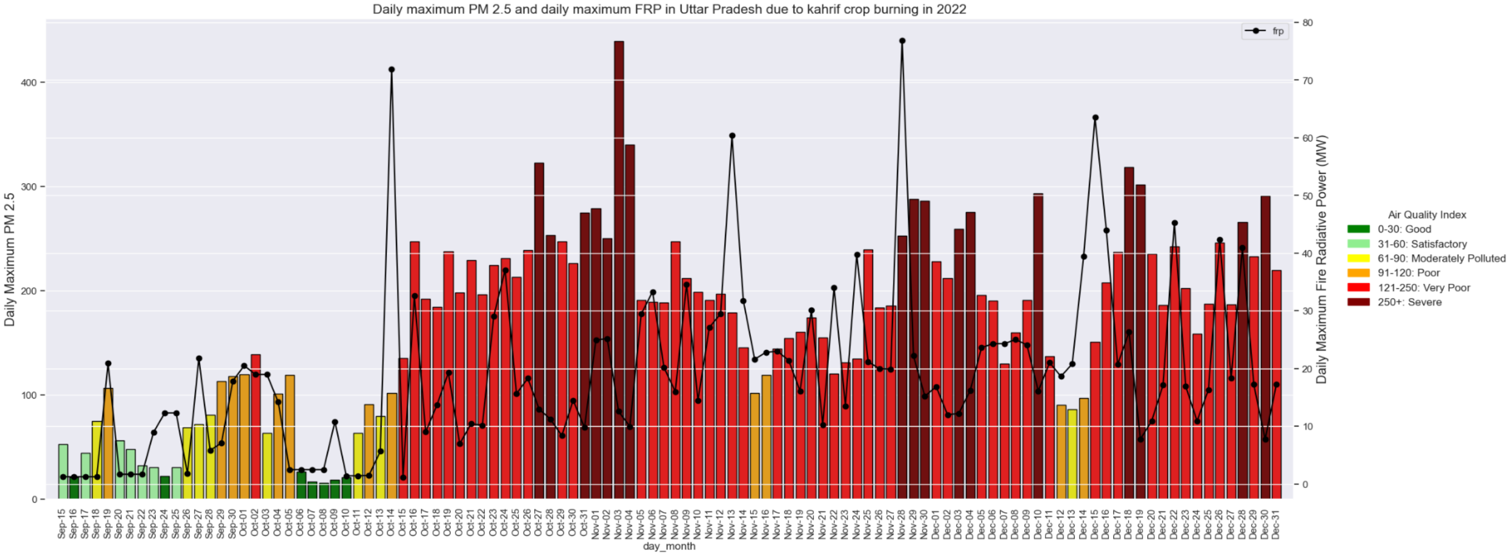


Fig 122: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2022

Figs 123 to Fig 128 shows the combined plot of FRP and PM2.5 concentration during the rabi crop burning in Punjab from 2018 to 2023

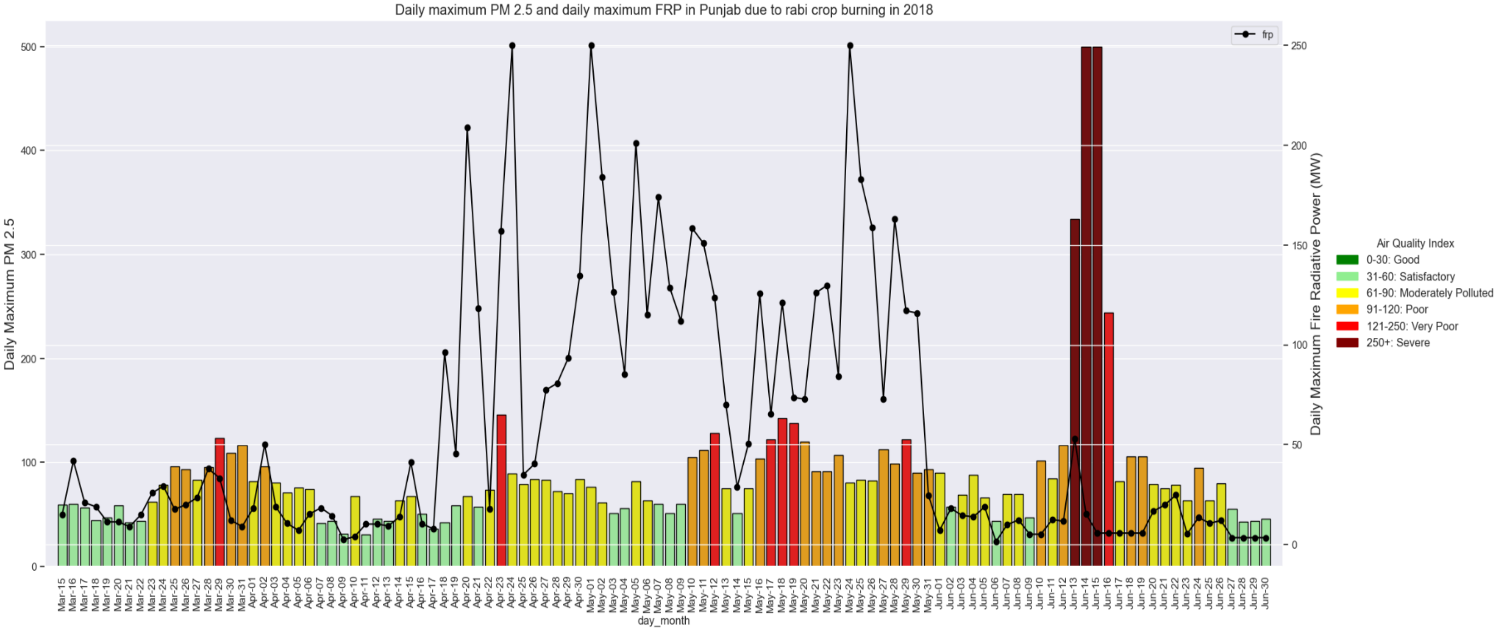


Fig 123: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2018

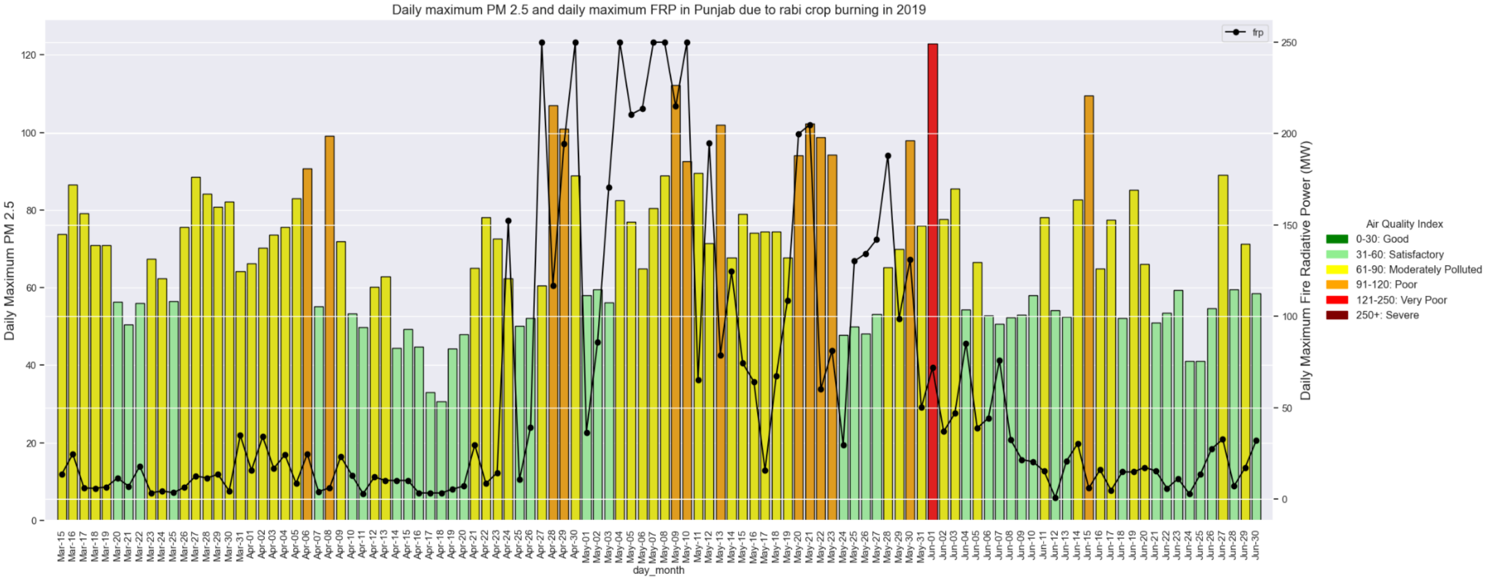


Fig 124: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2019

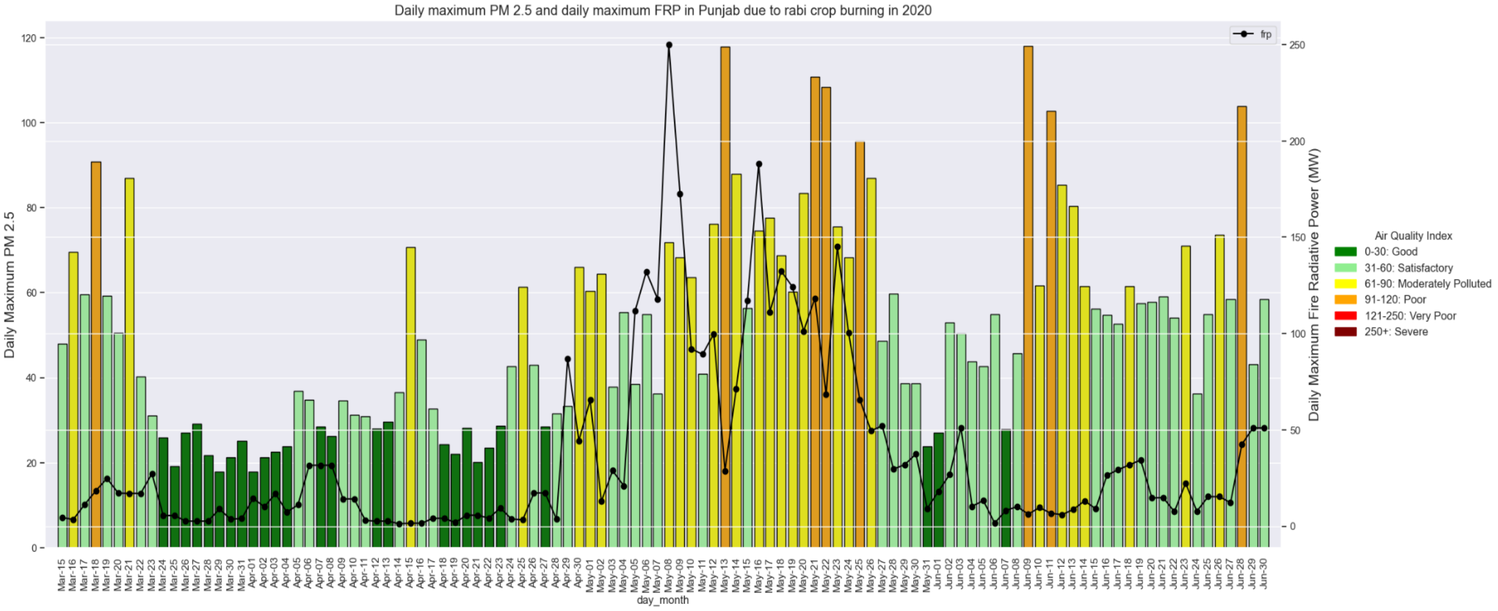


Fig 125: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2020

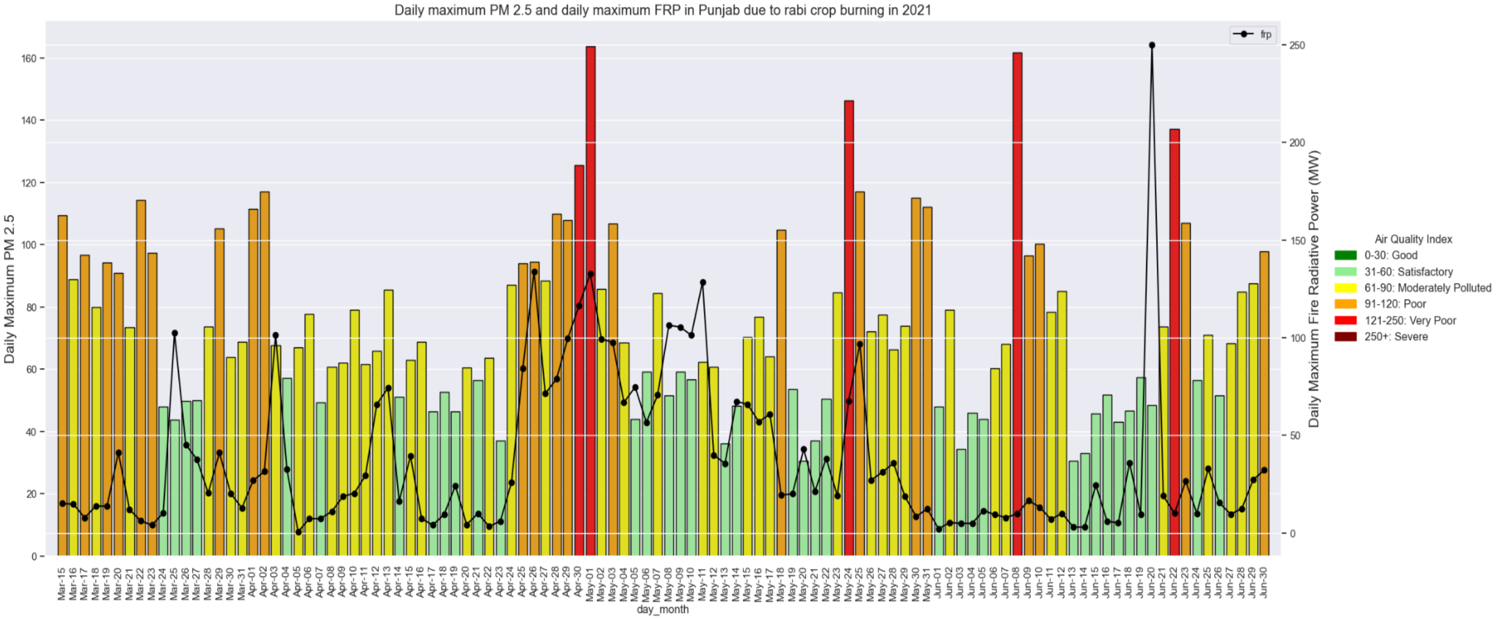


Fig 126: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2021

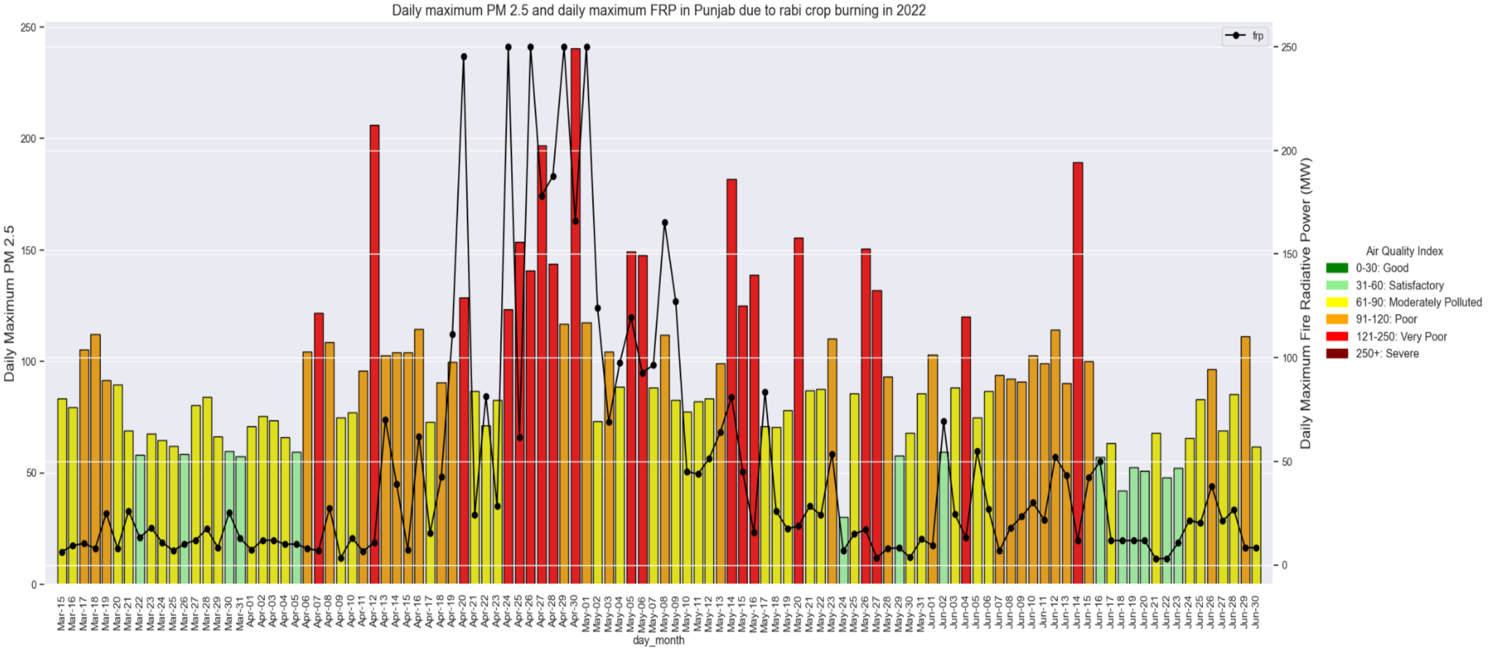


Fig 127: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2022

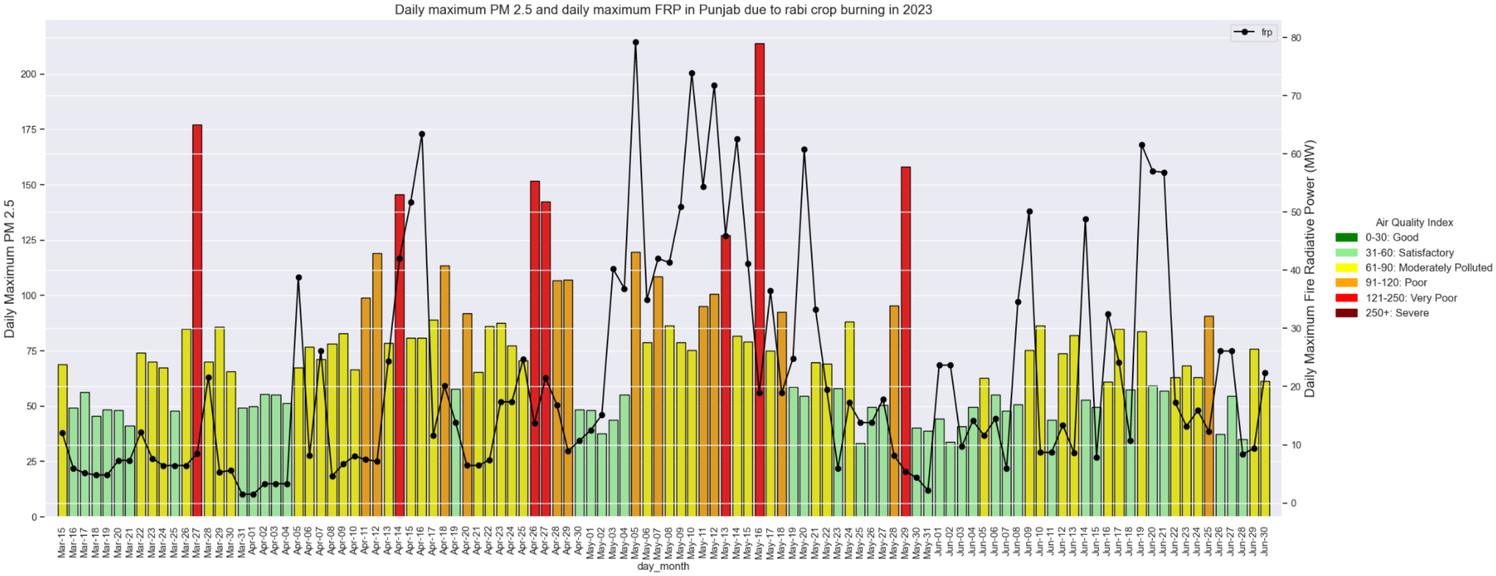


Fig 128: Daily maximum PM2.5 and daily maximum FRP in Punjab in 2023

Figs 129 to Fig 134 shows the combined plot of FRP and PM2.5 concentration during the rabi crop burning in Haryana from 2018 to 2023

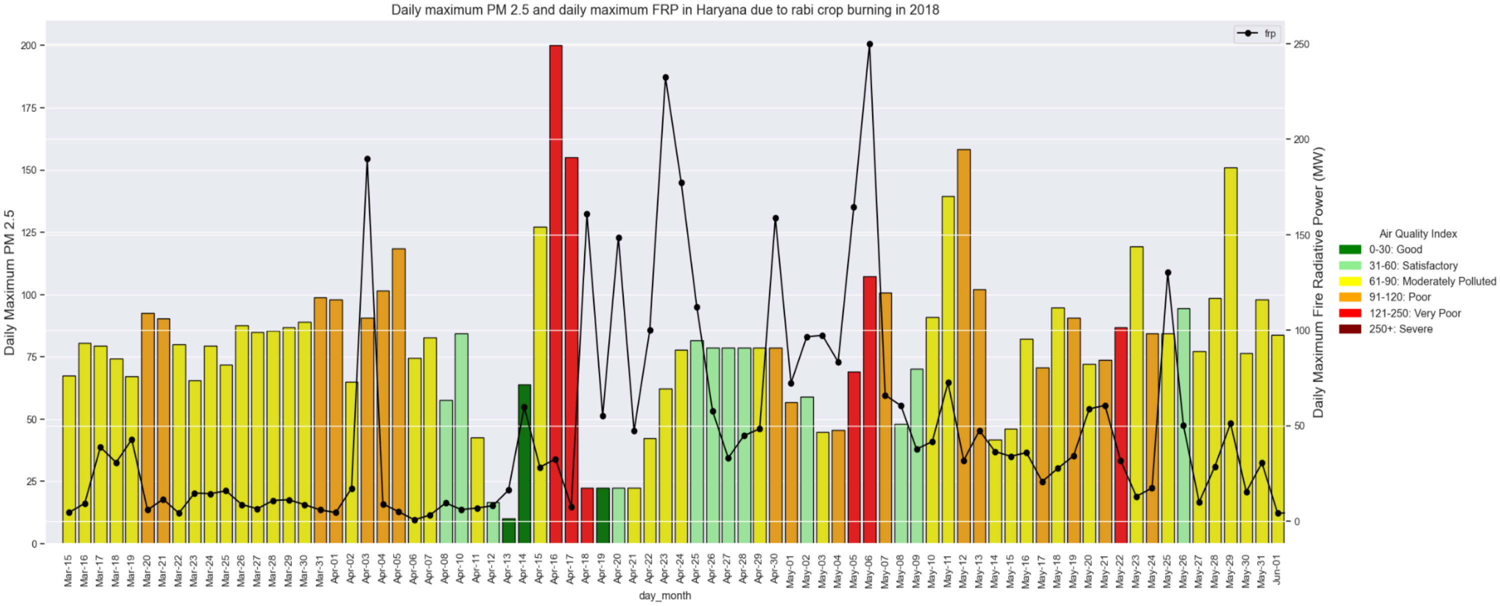


Fig 129: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2018

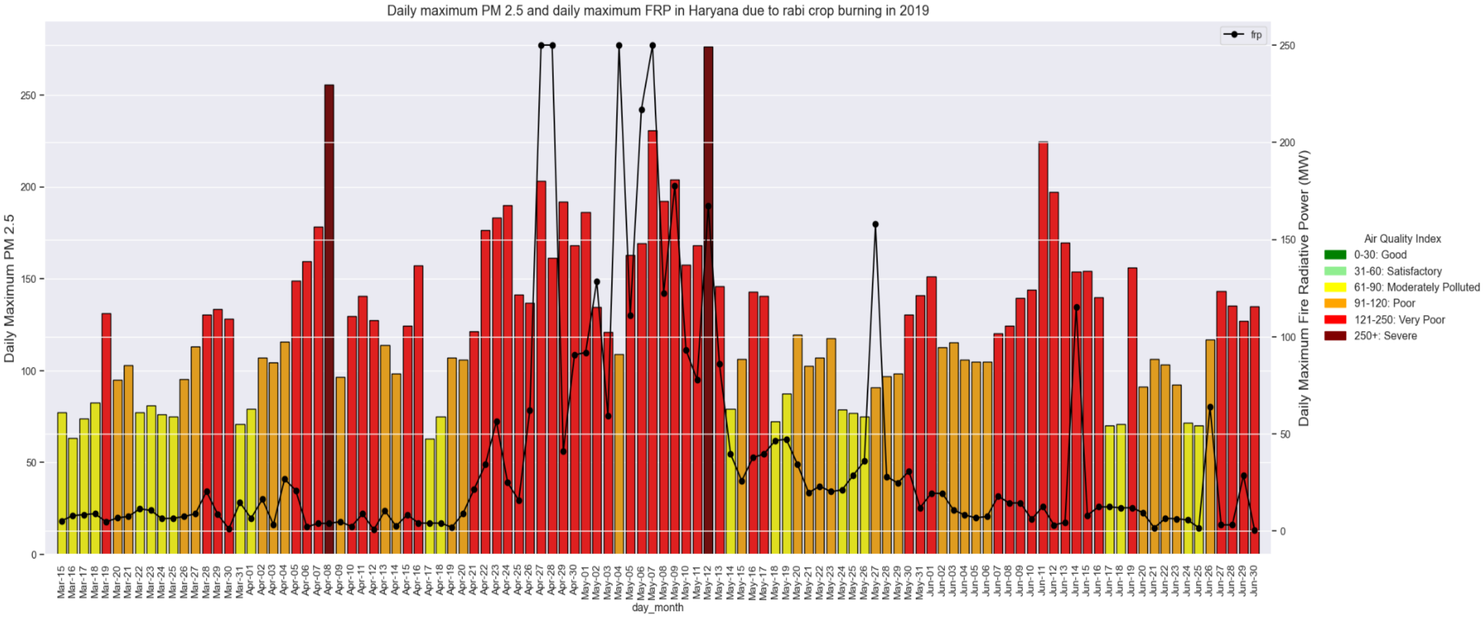


Fig 130: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2019

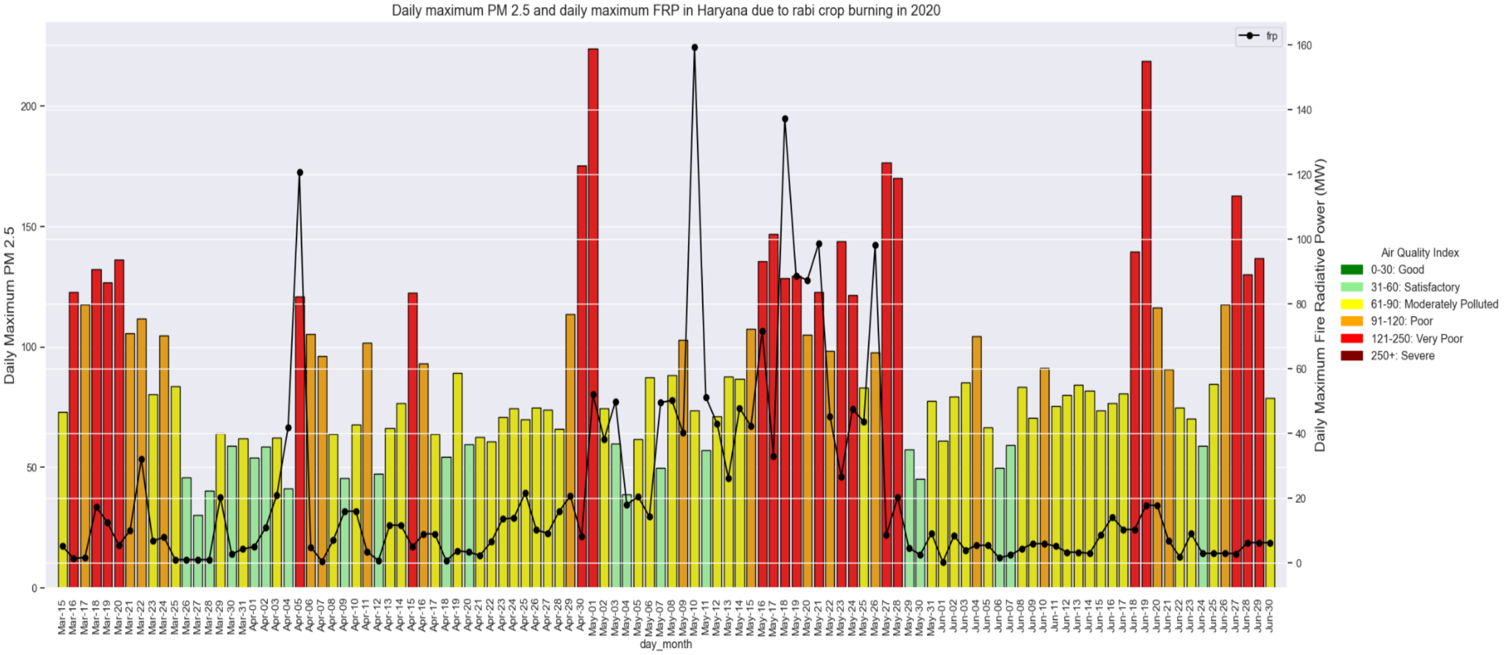


Fig 131: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2020

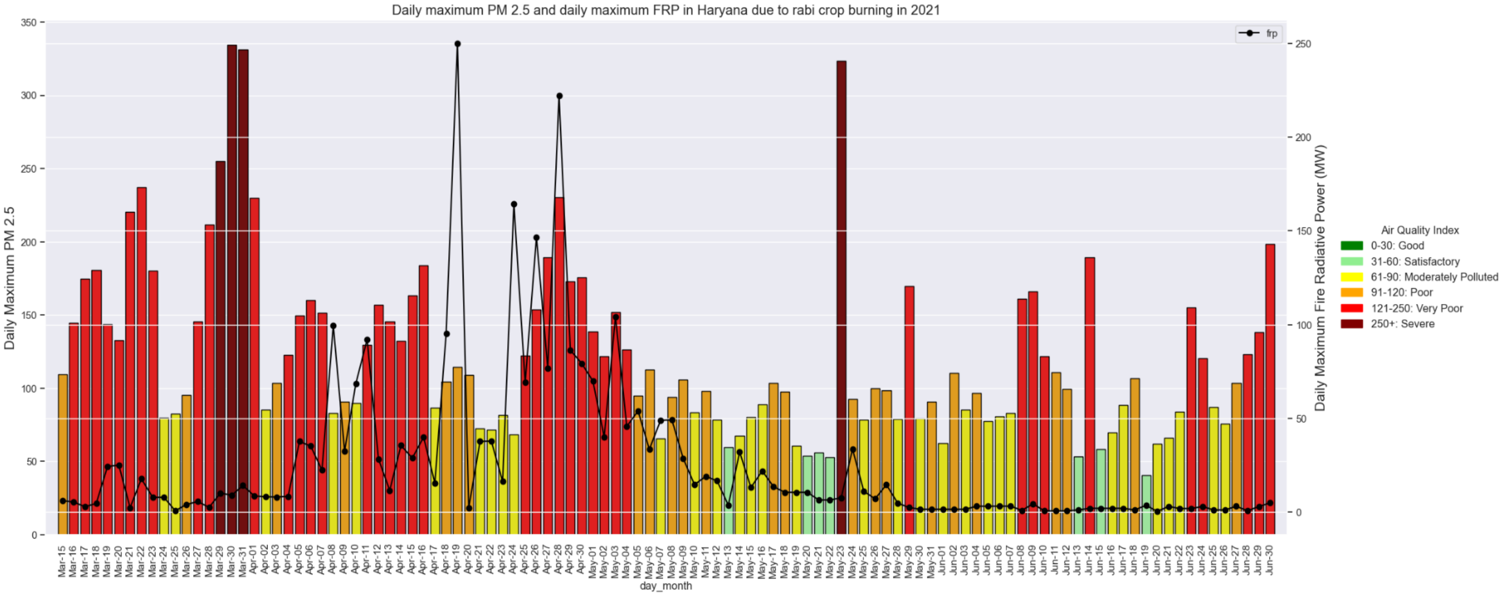


Fig 132: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2021

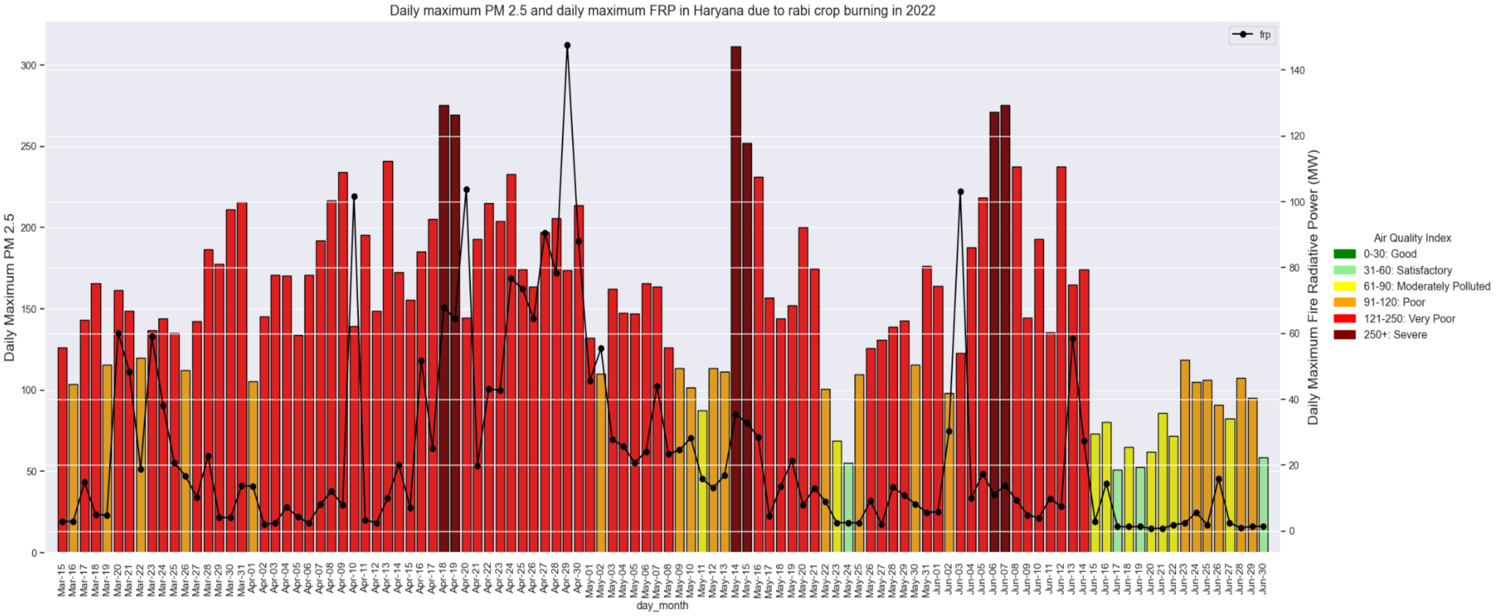


Fig 133: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2022

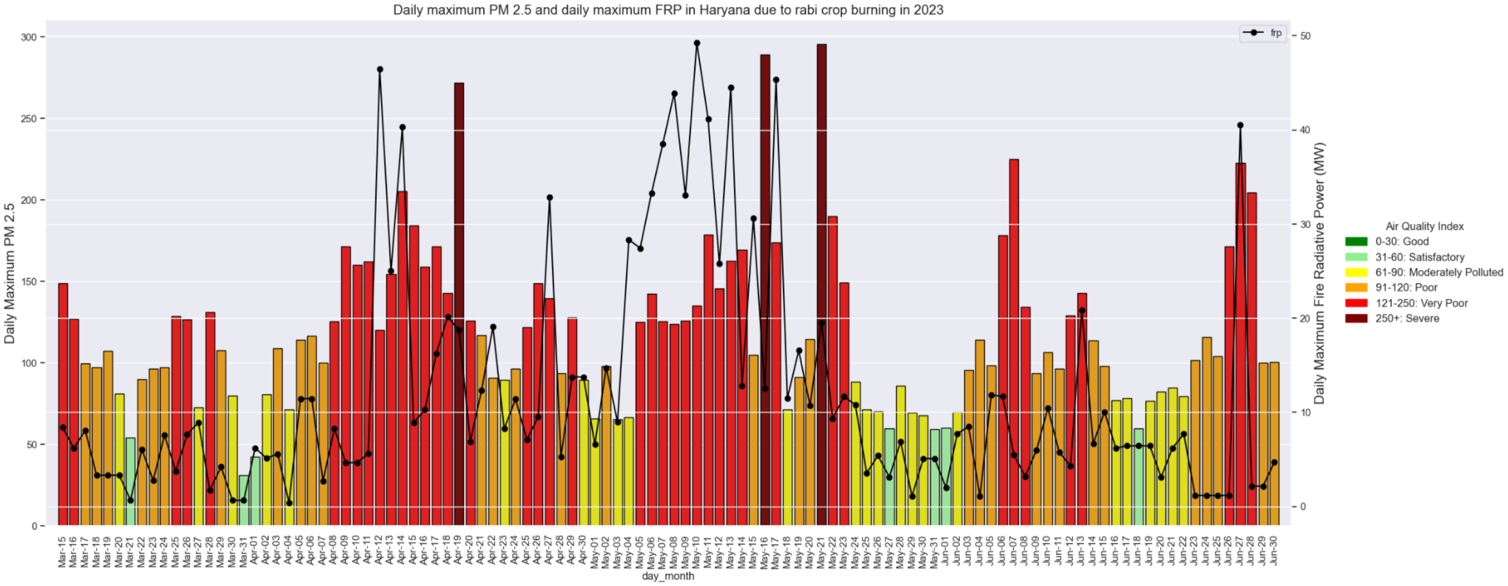


Fig 134: Daily maximum PM2.5 and daily maximum FRP in Haryana in 2023

Figs 135 to Fig 140 shows the combined plot of FRP and PM2.5 concentration during the rabi crop burning in Uttar Pradesh from 2018 to 2023

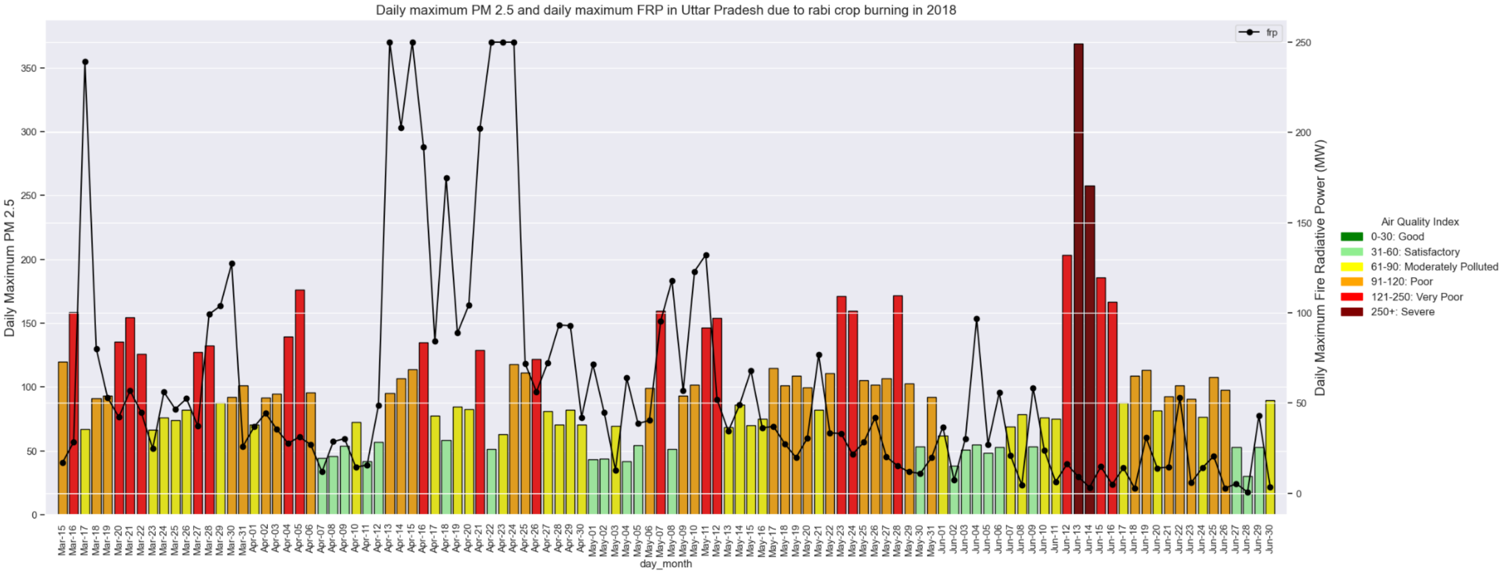


Fig 135: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2018

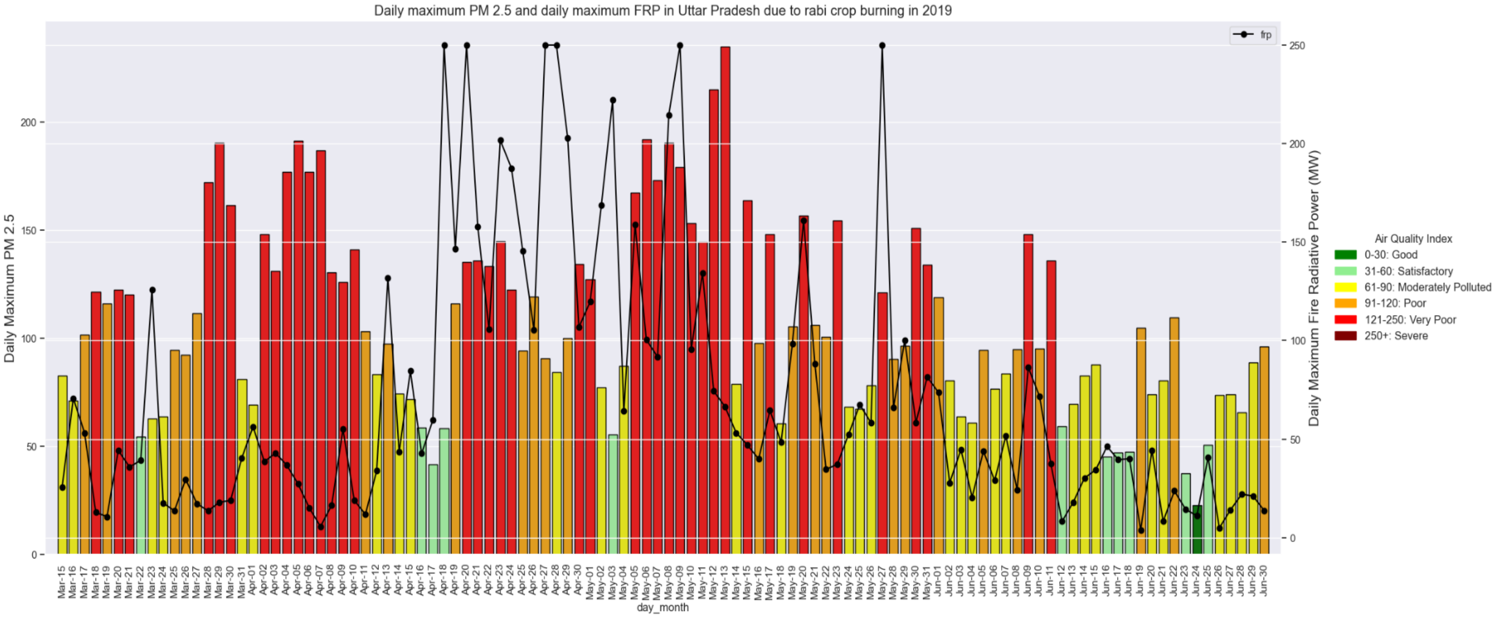


Fig 136: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2019

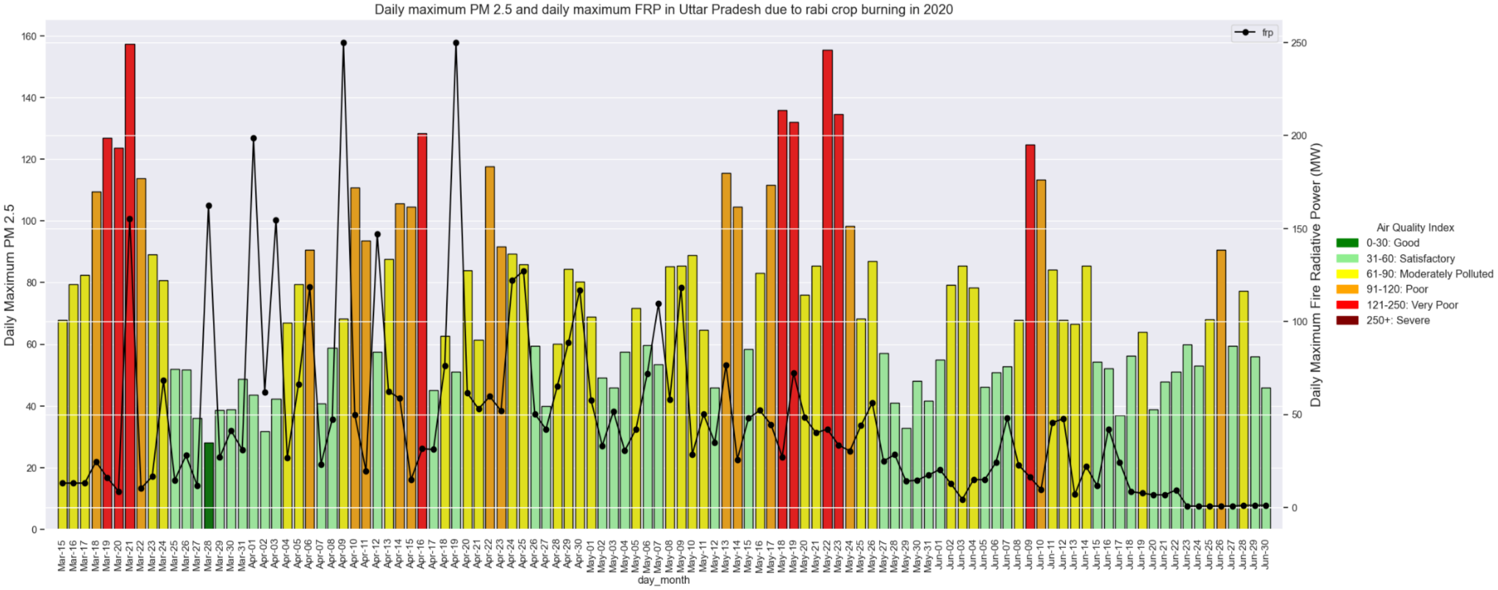


Fig 137: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2020

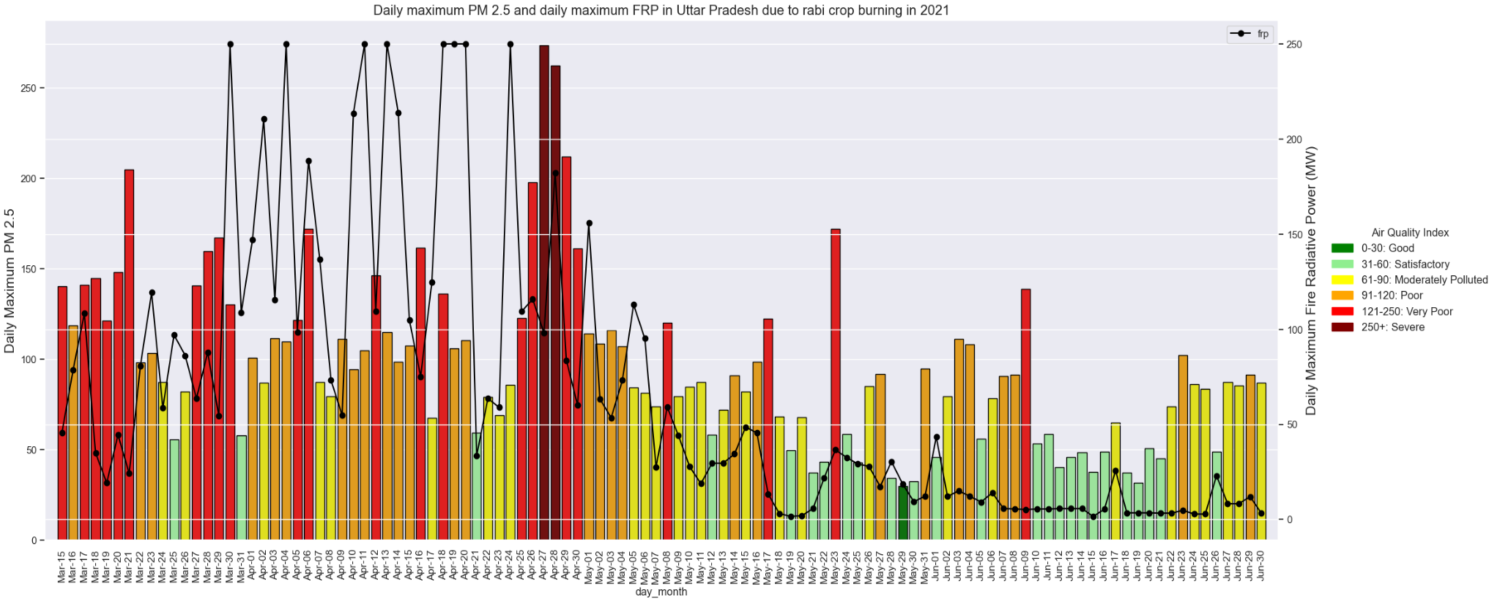


Fig 138: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2021

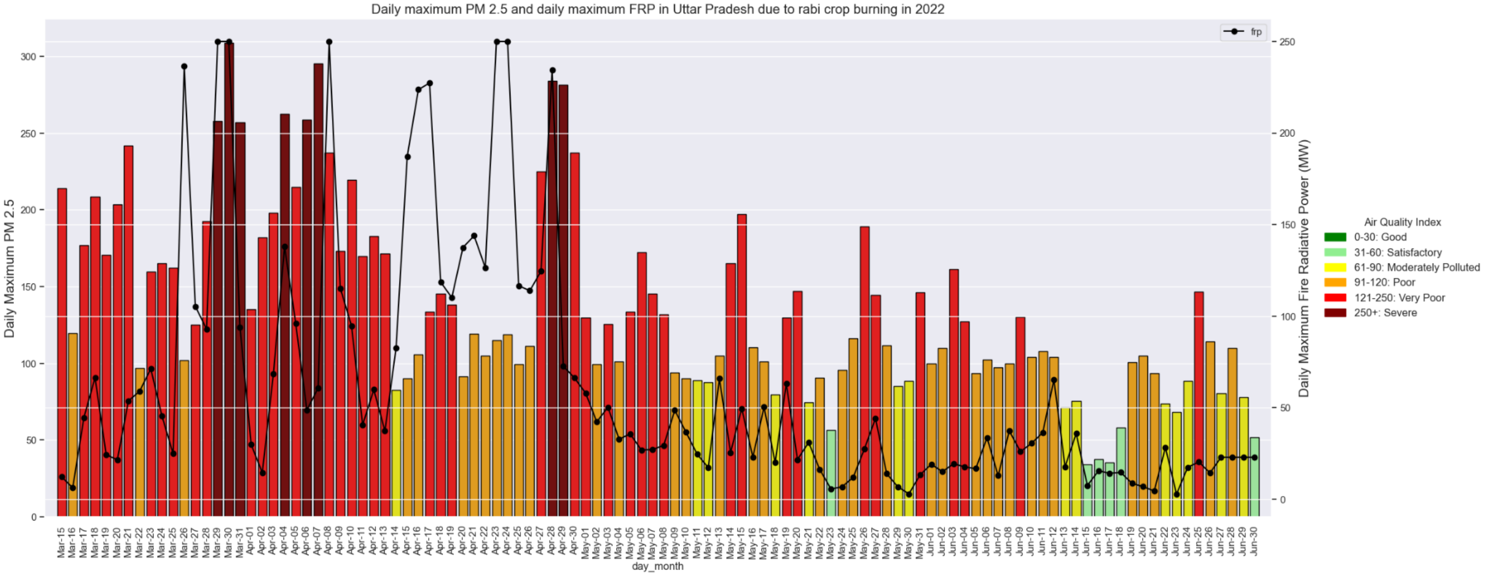


Fig 139: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2022

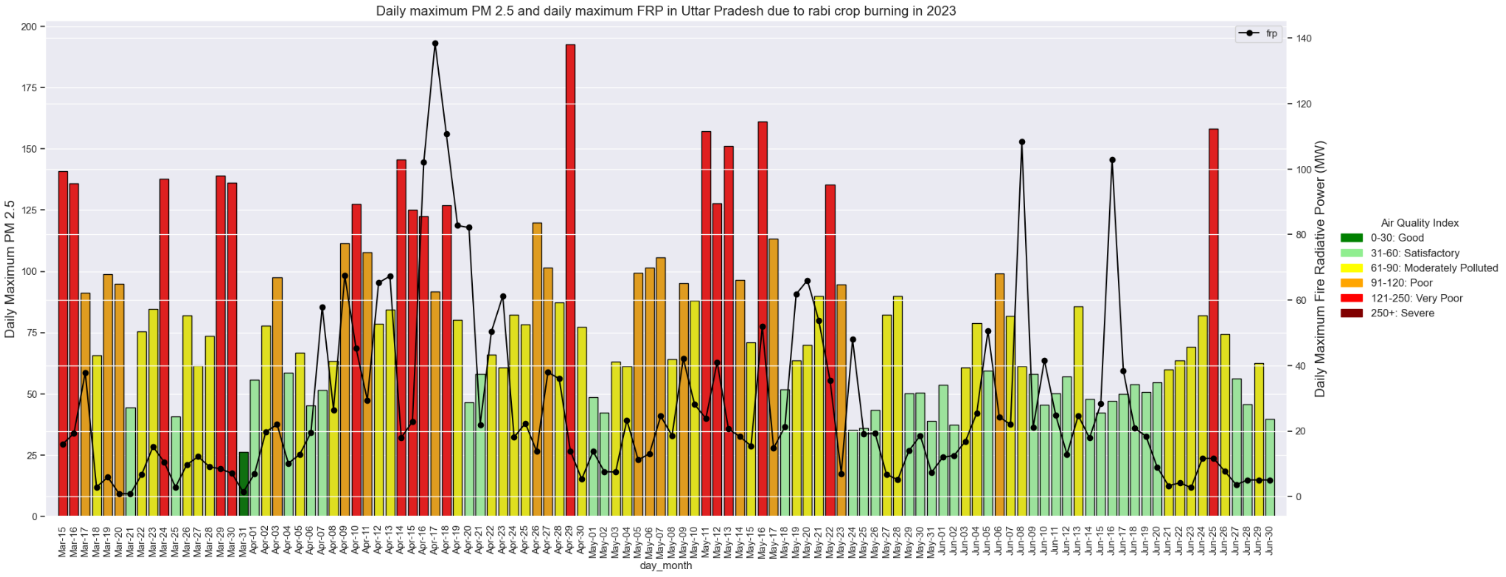


Fig 140: Daily maximum PM2.5 and daily maximum FRP in Uttar Pradesh in 2023

In the analysis, it becomes evident that in the years 2019 and 2021, particularly in December, PM2.5 concentration exhibited poor air quality levels even in the absence of stubble burning in Punjab. Similar instances were observed in the years 2019, 2020 and 2021 in Haryana and 2021 in Uttar Pradesh. It's crucial to acknowledge that multiple factors influence air quality, including emissions from vehicles, industrial pollutants and other sources. Punjab, for instance, hosts 13,092 factories spanning various industries, contributing significantly to air quality degradation. Similarly, from our study we found that Haryana, Uttar Pradesh and Delhi also host 11252, 16184 and 3259 factories within the state respectively.

Moreover, it's noteworthy that stubble burning often coincides with declining temperatures and slow wind speeds typical during the kharif crop burning season. These conditions can lead to temperature inversions, a phenomenon where normal atmospheric conditions are inverted, trapping smoke and pollutants in the lower atmosphere.

In our continued research, we aimed to analyze which districts implemented different policies to reduce crop burning, and which of these districts saw the most and least reduction in stubble burning activities from 2021 to 2022 and 2023.

Figs 109 to Fig 111 shows the decrease in stubble burning (in percentage) activities in Punjab.

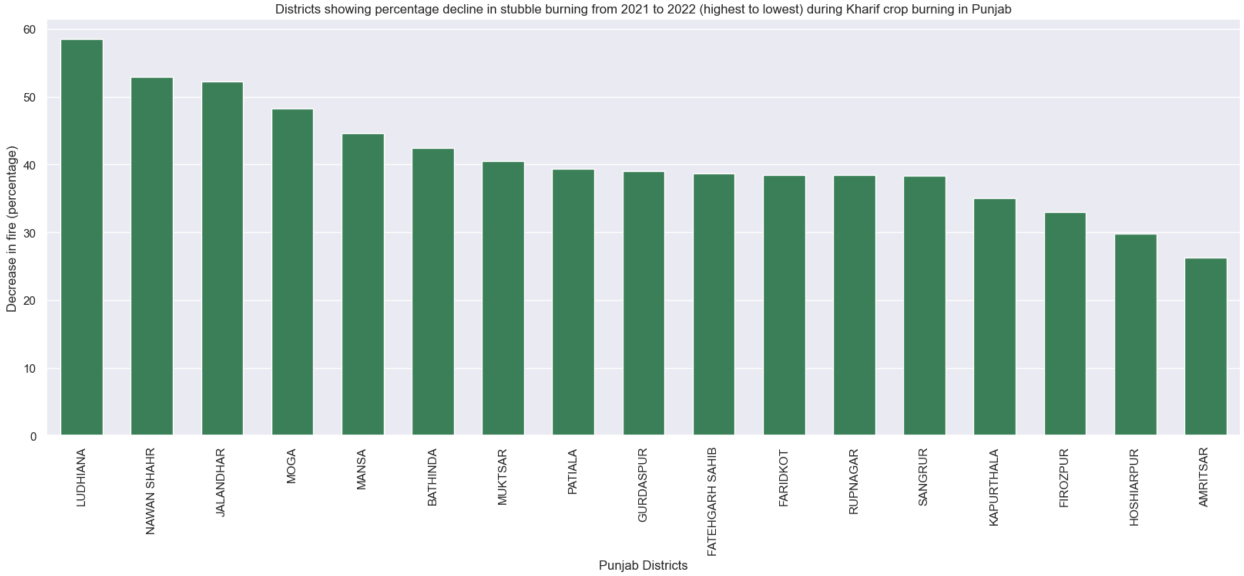


Fig 109: District Wise reduction in stubble burning in 2022 from 2021 in Punjab after kharif season

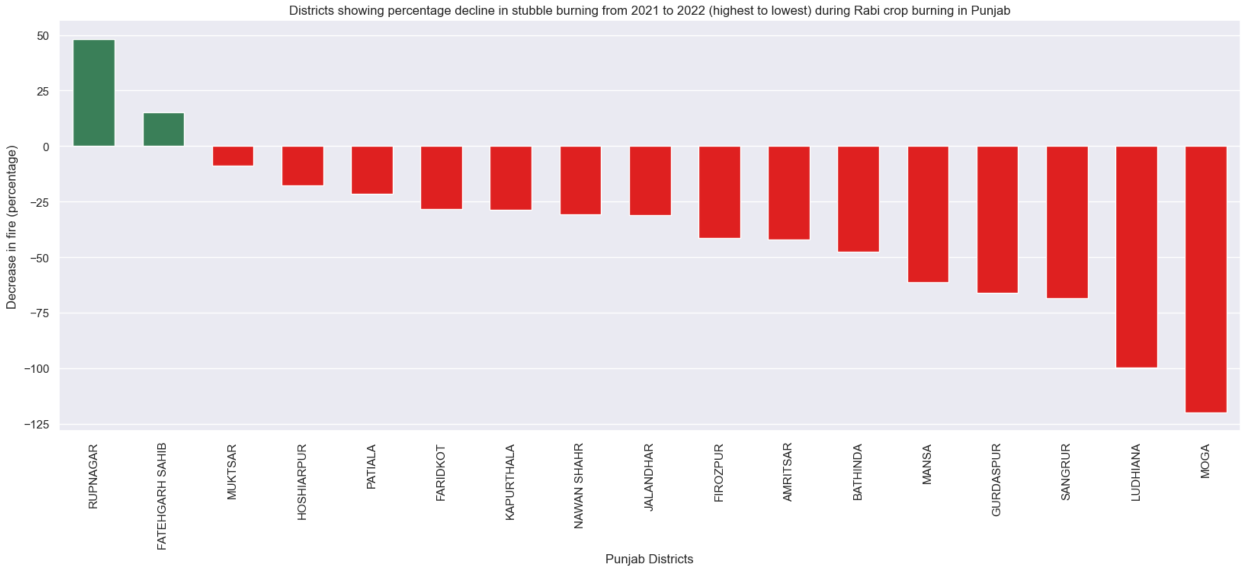


Fig 110: District Wise reduction in stubble burning in 2022 from 2021 in Punjab after rabi season

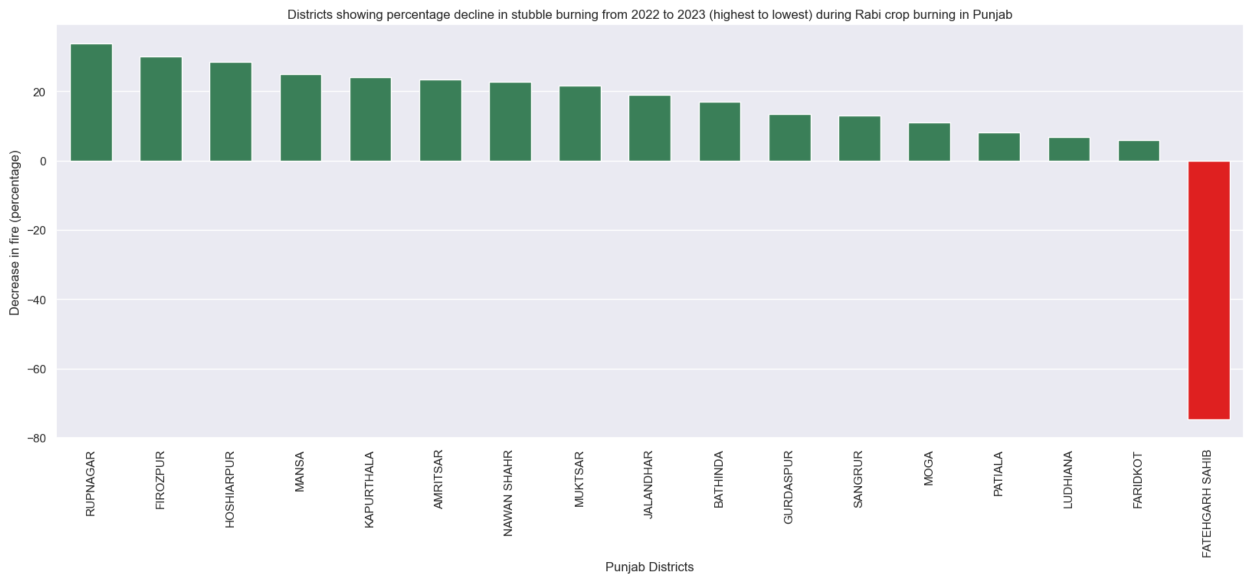


Fig 111: District Wise reduction in stubble burning in 2023 from 2022 in Punjab after rabi season

In Punjab, when we looked at the time when farmers burn crop residue after the kharif crop season, we found that in Ludhiana, Nawan Shahr and Jalandhar, there was a significant reduction of over 50% in stubble burning activities in the year 2022 compared to 2021.

Similarly, during the rabi crop burning season we noticed changes in different districts. For example, in Rupnagar, there was an average decrease of about 35% in stubble burning activities in 2023 compared to 2021. On the other hand, Fatehgarh Sahib saw a notable increase of more than 50%in stubble burning activity in 2023 compared to 2022.

Fig 112 to Fig 114 shows the decrease in stubble burning (in percentage) activities in Haryana

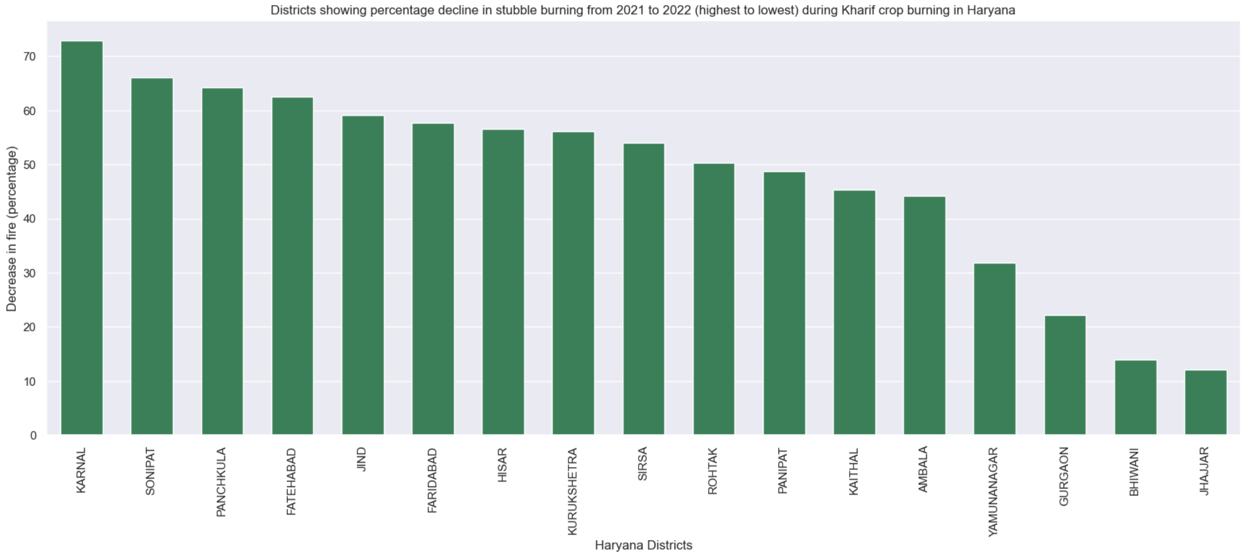


Fig 112: District Wise reduction in stubble burning in 2022 from 2021 in Haryana after kharif season

Fig 113: District Wise reduction in stubble burning in 2022 from 2021 in Haryana after rabi season

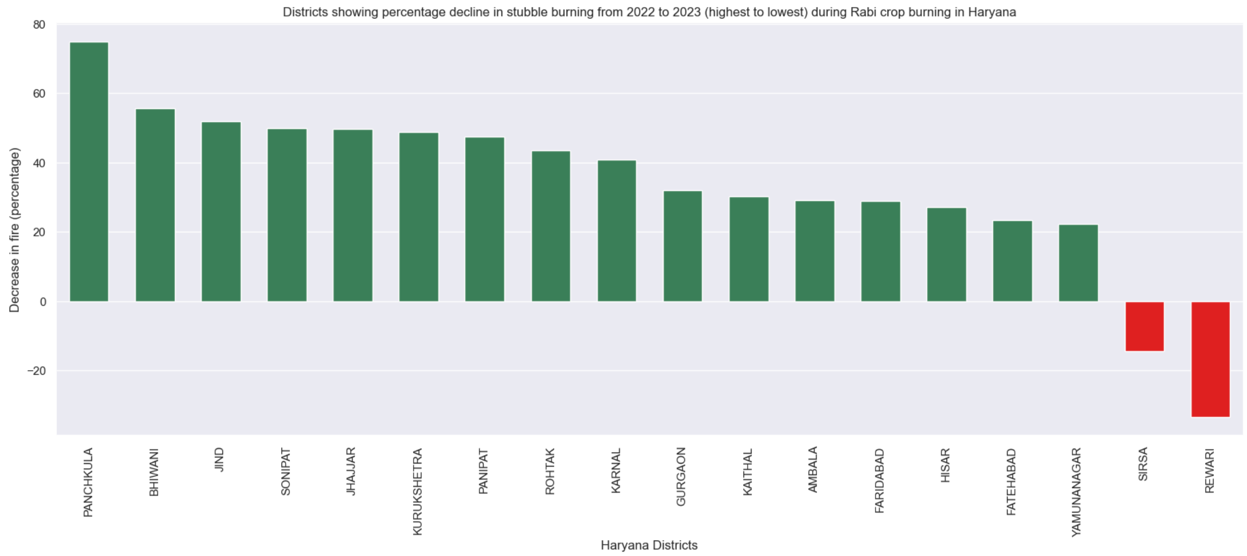


Fig 114: District Wise reduction in stubble burning in 2023 from 2022 in Haryana after rabi season

In Haryana, we noticed significant changes in burning activities after the kharif crop season. Districts like Karnal, Sonipat, Panchkula and Fatehabad saw a substantial decrease of more than 60% in stubble burning in the year 2022 compared to 2021. Surprisingly, Fatehabad also showed an increase of more than 50% in stubble burning activity after the rabi crop season in the same year. Additionally, we found that Panchkula, Bhiwani, Jind and Sonipat experienced a decrease of about 50% in stubble burning activities in 2023 compared to 2022.

Figs 115 to Fig 117 shows the decrease in stubble burning (in percentage) activities in Uttar Pradesh

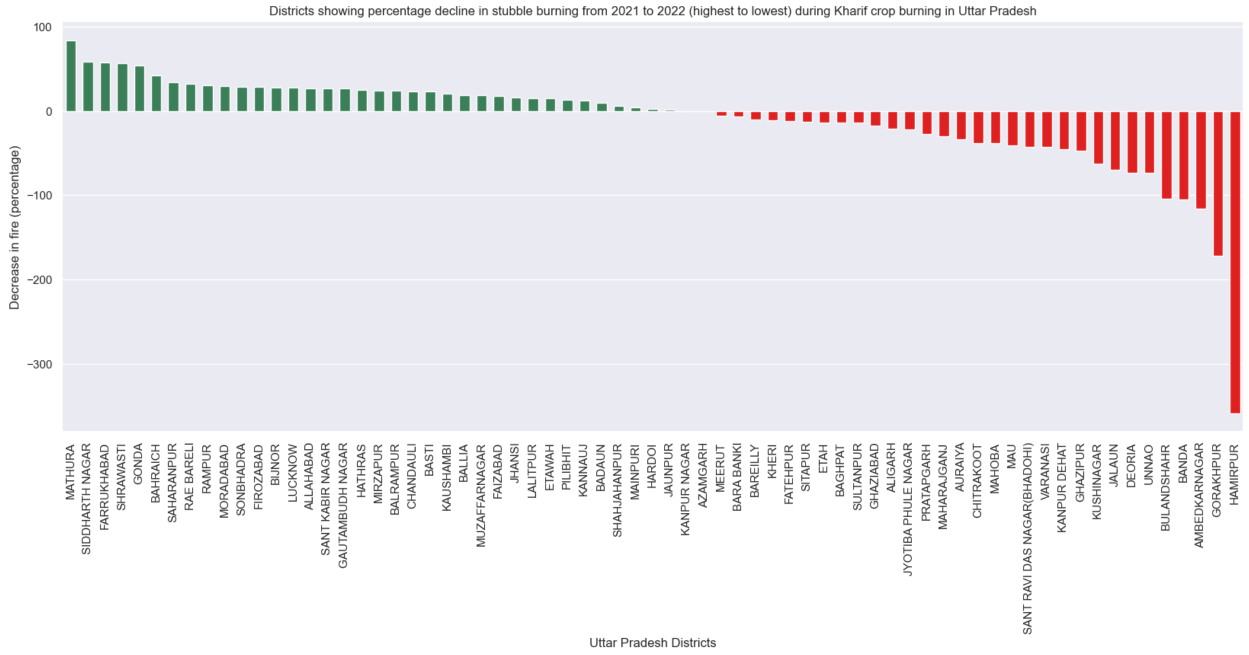


Fig 115: District-Wise reduction in stubble burning in 2022 in UP after kharif season

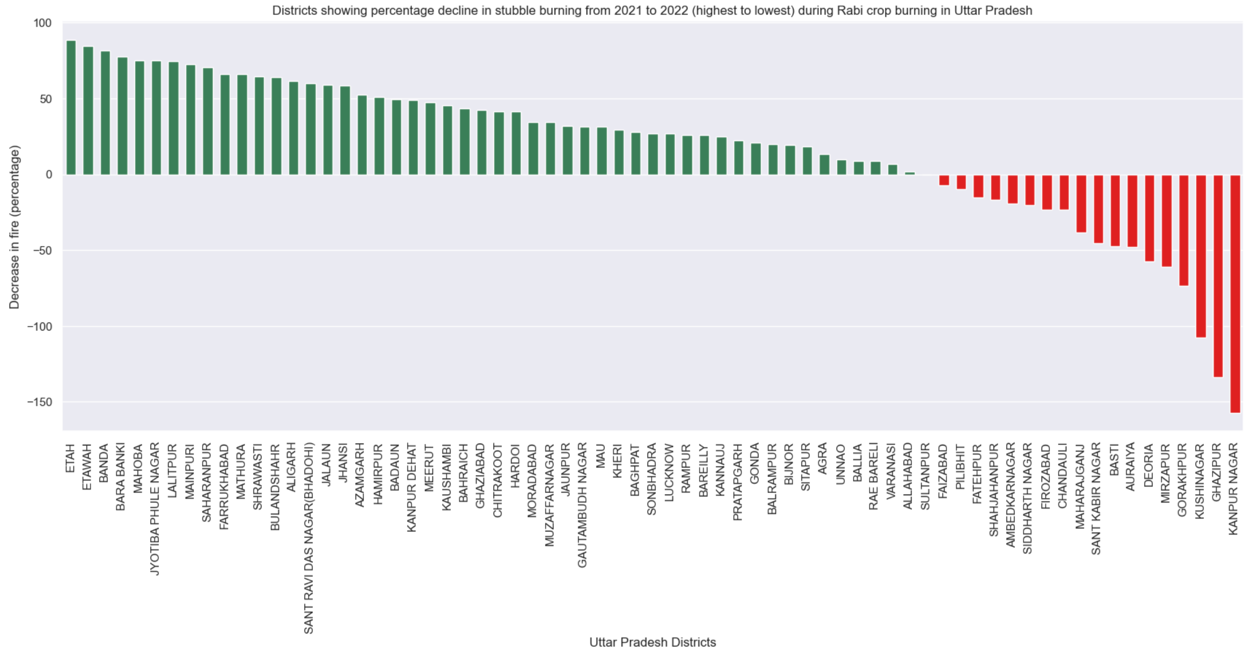


Fig 116: District-Wise reduction in stubble burning in 2022 in UP after rabi season

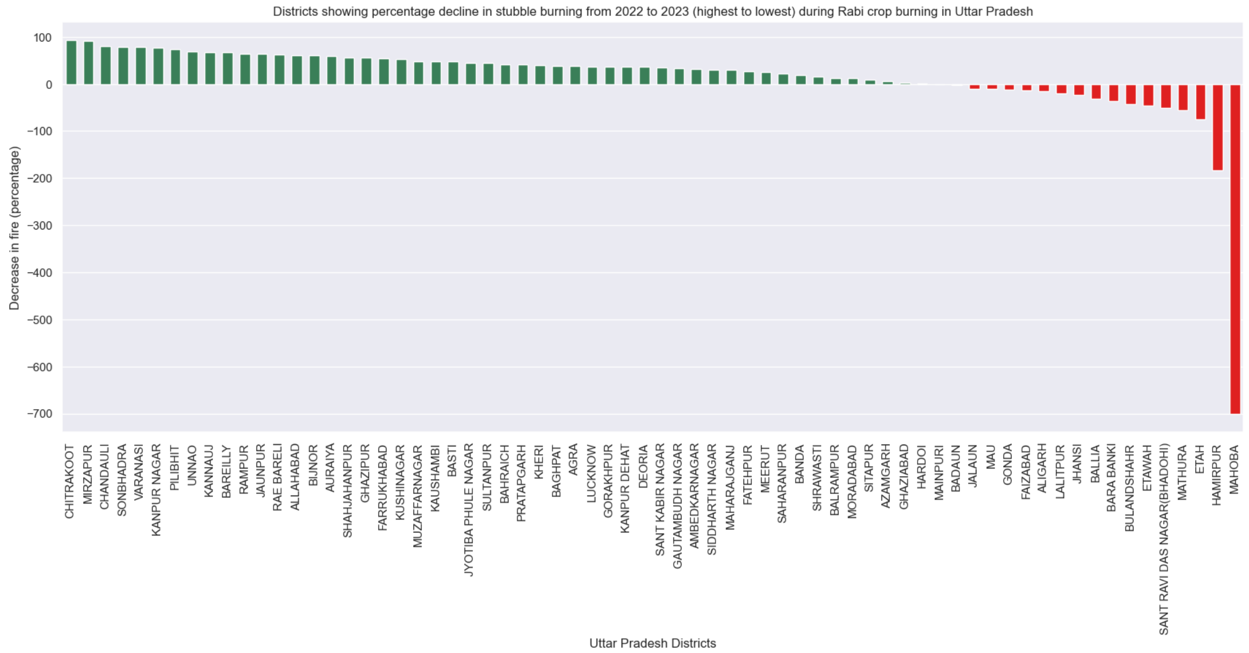


Fig 117: District Wise reduction in stubble burning in 2023 from 2022 in Uttar Pradesh after rabi season

In Uttar Pradesh, some interesting trends emerged during the stubble burning analysis. After the kharif crop season in 2022, districts like Mathura witnessed a significant decrease of more than 60% in burning activities compared to 2021. Siddharth Nagar and Farrukhbad also showed around a 50% reduction in stubble burning.However, in the same cro season, Hamirpur experienced a startling increase of about 300% in burning incidents, followed by Gorakhpur, where it went up by approximately 150%.

During the rabi crop burning season, Etah, Etawah and Banda saw a substantial decrease of more than 70% in 2022 compared to 2021. But it’s noteworthy that in the following year Etah and Etawah recorded an increase in stubble burning from 2022.

Mahoba stood out with a significant increase of 700% in fire activities in 2023 compared to 2022, Gazipur and Kanpur also showed increases of more than 150%.

Conclusion

In conclusion, our research paper has shed light on the impacts of stubble burning on air quality of Punjab, Haryana and Uttar Pradesh. By analysing the temporal and spatial distribution of fire radiative power and PM2.5 concentration, we found that there is a significant impact on air quality during Kharif and Rabi seasons. We have also related it with policies implemented on stubble burning activities at district level. Many new national and international research findings and methods have come out or have been adapted in Punjab to support the agricultural sector. Our suggestions would be to strengthen the local research institutions to conduct research to identify and adapt to depleting labour, irrigation, and soil conditions. The soil type of Punjab varies across the state, so state recommendation on favoring plants and crop based on their yield capacity needs to be assessed. This study also presents an opportunity for the research community to hypothesize, understand and recommend solutions to farmers on how to move away from a monocycle cereal system to a sustainable crop cycle which factors in the site situation (soil quality, water resources, labour, and planting dates) and also yields good results economically. The research on climate change adaptation needs to not only focus, on understanding the linkages between the various factors but also on finding solutions, particularly from policy output perspectives. In addition, research aimed at understanding the various interventions and interlinkages should also be encouraged to facilitate in filling up the gap between science, policy, and practice.

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