Journal of Climate Change, Vol. 9, No. 2 (2023), pp. 43-53.
DOI 10.3233/JCC230014

Unraveling the Relationship Between Stubble Burning and Air Quality Degradation in Punjab: A Temporal and Spatial Analysis (2019-2022)

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Received May 10, 2023; revised and accepted May 31, 2023

Abstract: Stubble burning in Punjab, India, poses significant environmental challenges, particularly impacting air quality. This study aims to examine 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. The Inverse Distance Weighting (IDW) interpolation technique was used to estimate pollution values in areas lacking direct monitoring. The study revealed significant year-to-year variations in areas affected by stubble burning. 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 analysed, peaking in 2021. The spatial and temporal variations of stubble burning events and their relationship with air quality highlight the need for targeted interventions. Understanding these patterns is crucial for mitigating the adverse effects of stubble burning on air quality in Punjab, India. Future research should focus on evaluating the effectiveness of various mitigation strategies.

Keywords: Stubble burning; Air quality; Punjab; PM2.5; PM10; Sentinel-2; Normalised burn ratio; Inverse distance weighting.

Introduction

Stubble burning, a pervasive agricultural practice that involves the deliberate incineration of crop residues following the harvest of grains, has been globally acknowledged as a major contributor to atmospheric pollution (Andreae et al., 2001). This practice is commonly implemented following the harvest of grains

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such as paddy, wheat, rice, corn, and other crops, and has significant consequences for both local and global environments (Cao et al., 2008). The burning process emits a vast array of particulate and gaseous pollutants that have been scientifically linked to a variety of adverse effects on both human health and broader ecosystems (Chawla et al., 2020).

Among the direct impacts of stubble burning are depletion of soil nutrients (nitrogen, phosphorus, potassium, and sulphur) from the uppermost topsoil layer and a reduction in soil organic matter. This degradation of soil health in turn leads to declines in agricultural production and productivity, creating an unsustainable cycle of soil degradation and lower crop yields (Gadde et al., 2009). The pollutants emitted by stubble burning can degrade air quality, which in turn leads to biodiversity loss, detrimental effects on water and energy efficiency, and serious health impacts on both human and animal populations. These issues have a wider societal impact, contributing to health inequality and economic instability (Hooda et al., 2014).

On a global scale, the trend of stubble burning is on the rise, influenced by factors such as increased mechanisation in agriculture, labour shortages, and a dearth of viable and affordable alternatives for crop residue management (Durin et al., 2022). 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 2017. These incidents predominantly occurred during the post-harvest seasons, underscoring the link between agricultural practices and increased fire incidents (Singh et al., 2022).

A substantial body of research has delved into the impacts of stubble burning on air quality and human health. These studies have consistently demonstrated a strong correlation between stubble burning practices and elevated levels of air pollution, particularly in relation to PM2.5, PM10, and other hazardous pollutants (Chawala et al., 2020). This increased pollution has been linked to a rise in morbidity and mortality rates due to respiratory and cardiovascular diseases, emphasizing the public health implications of this agricultural practice (Gupta et al., 2004).

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, high-resolution Sentinel-2 satellite imagery, with its multispectral capabilities, has proven effective in the timely detection and mapping of stubble burning, providing invaluable data to researchers and policymakers (Meraj et al., 2022). However, there is still a need for further research into the potential applications of Sentinel-2 data, particularly in relation to monitoring stubble burning in Punjab and assessing its impact on ambient air quality (Murphy et al., 2008).

Despite the valuable insights provided by previous studies, which have utilized remote sensing techniques to monitor stubble burning and its impacts on air quality, there is still a notable gap in research that specifically employs high-resolution Sentinel-2 imagery for this purpose in Punjab (Singh et al., 2021). Given the scale of the issue in this region, there is a clear need for a focussed investigation into this particular context. Therefore, this study aims to analyze the spatial distribution and temporal patterns of stubble burning in Punjab and to assess the relationship between these burning events and ambient air quality in the region. By offering a more in-depth understanding of the extent and implications of stubble burning in Punjab, this study hopes to contribute to the development of effective mitigation strategies, potentially providing a model for similar agricultural regions around the world (Sandhu et al., 2018).

Study Area

The focus of this study is the state of Punjab, situated in the northern region of India, demarcated by geographical coordinates of 29.5-32.5°N latitude and 73.9-76.8°E longitude. Spanning an area of about 50,362 square kilometers, Punjab supports a population of 31,623,274. The state is encompassed by the Indian states of Haryana, Himachal Pradesh, and Rajasthan, as well as the Pakistani province of Punjab. It is widely celebrated as the "Granary of India" due to its fertile agricultural landscape that significantly contributes to the country's overall food production. The geographical layout of the study area is demonstrated in Figure 1.

Punjab boasts a diverse topography, transitioning from the fertile alluvial plains of the Indus River system in the east to the Shivalik Hills' undulating terrains in the north. The climate of Punjab is categorised into three distinct seasons: the blistering summer season (April to June), the rain-driven monsoon season (July to September), and the cooling winter season (October to March). The time frame of this study, namely October and November, aligns with the post-

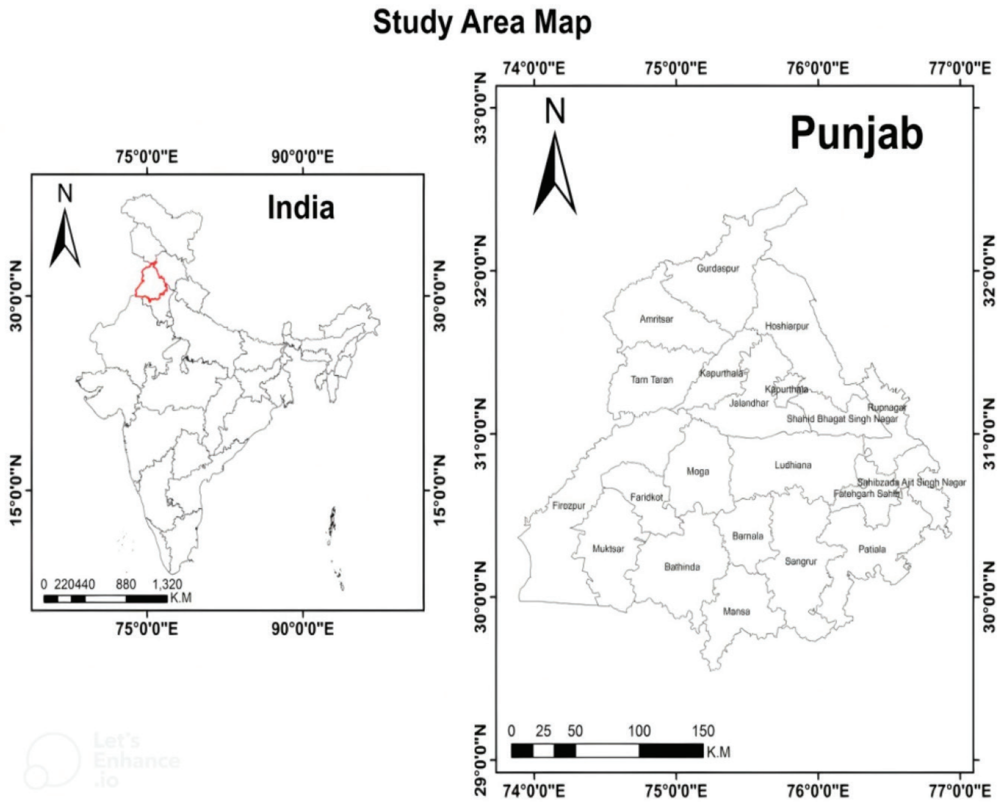

Figure 1: Study area map showing the state of Punjab.

monsoon period when temperatures start to descend, and agricultural activities such as harvesting and crop residue management begin to ensue.

Agriculture is the central pillar of Punjab's economy, with the state distinguishing itself as a premier producer of staple crops, including wheat, rice, and maize. The intensified agricultural practices combined with mechanised harvesting techniques have led to a considerable rise in crop residue. This leftover crop residue is often disposed off through burning, which has transformed Punjab into a significant hub for stubble burning events. These events, in turn, contribute heavily to air pollution and have deleterious repercussions on human health and the surrounding environment (Pradhan et al., 2001).

The frequency of stubble burning and the associated effects on air quality makes Punjab a pertinent region of study for this research. By investigating the spatial and temporal patterns of stubble burning events and assessing their possible correlation with ambient air quality in Punjab, this study seeks to deliver invaluable insights. These insights could guide the formulation of efficient management strategies and mitigation efforts to confront this pressing environmental issue.

Materials and Methodology

Data Used

This study relied on various data sources to meticulously analyse stubble burning events and comprehend their subsequent impact on air quality in Punjab. The data sources involved in this research are summarised in Table 1. To discern and monitor stubble burning incidents, we relied on Sentinel-2 satellite imagery, which enabled a detailed and precise identification of burnt areas. To understand the after effects of stubble burning on the air quality, we used air quality data, specifically PM2.5 and PM10 concentrations, derived from the Punjab Pollution Control Board (PPCB). Figure 2 displays PPCB monitoring stations that provided the crucial data.

Additionally, we incorporated the Climate Change Initiative Land Use Land Cover (ESA CCI LULC) dataset from the European Space Agency. This data was instrumental in isolating agricultural fields and helped us focus the analysis on the spatial distribution of stubble burning events within these specific areas. These varied data sources allowed for an exhaustive exploration of the spatial and temporal patterns of

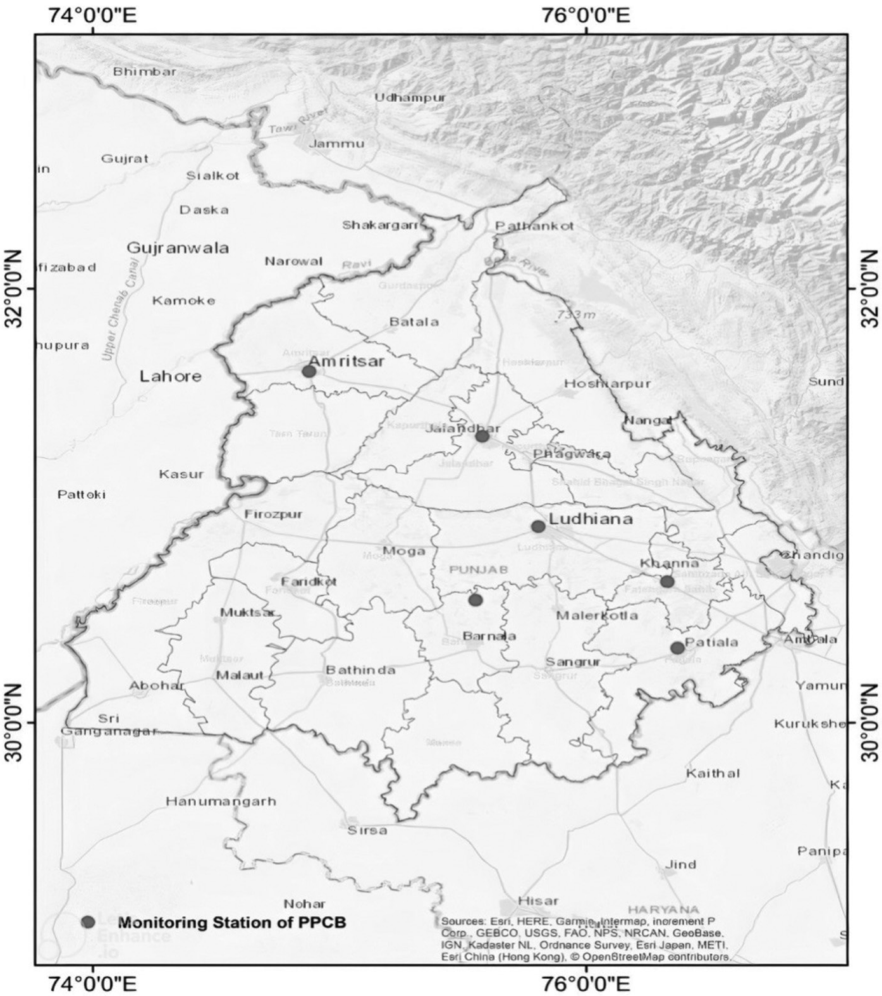

Figure 2: Air quality monitoring station PPCB.

stubble burning events and their potential influence on the ambient air quality in Punjab.

Table 1: Data used in the study

Data source	*Description*	*Spatial resolution*	*Year(s)*
Sentinel 2	High-resolution satellite imagery for stubble burning detection and monitoring	10m-20m	2019-2022
PPCB	Punjab Pollution Control Board data on air quality parameters (PM2.5 and PM10)	N/A	2019-2022
ESA CCI LULC	European Space Agency Climate Change Initiative Land Use Land Cover data for masking out agricultural fields	10m	2019-2022

Methods

The study's methodological framework consists of two central components: surveillance of stubble burning employing advanced remote sensing techniques and an evaluation of the ambient air quality. Each of these components is elucidated in detail below. Figure 3 shows the methodology flow chart of this study.

Stubble Burning Monitoring

For a comprehensive understanding of the spatial extent of stubble burning in Punjab from 2019 to 2022, we utilised high-resolution Sentinel-2 satellite imagery made available by the European Space Agency (ESA). The Sentinel-2 imagery, with a spatial resolution of 10 meters, is frequently deployed in various scientific and environmental applications due to its multi-spectral bands, high temporal and spatial resolution, and free availability.

Data Preprocessing

Given that stubble burning predominantly takes place during the post-harvest period, the study concentrated on the months of October and November for each year from 2019 to 2022. We processed the Sentinel-2 imagery into monthly composites using Google Earth Engine, a robust, cloud-based platform known for its capability to handle large-scale geospatial data efficiently. To maintain the quality of the composite, we applied a cloud filter to select images with less than 10% cloud cover. This process helped ensure the precision of the generated data and mitigate potential inaccuracies due to cloud interference.

Stubble Burning Detection

Our approach to identifying the burnt areas involved the calculation of the Normalized Burn Ratio (NBR) for each Sentinel-2 image. The NBR is a renowned remote sensing index used to track burn areas and is calculated using the near-infrared (NIR) and shortwave infrared (SWIR) bands of satellite imagery. These bands are particularly sensitive to changes in vegetation and moisture content (Murphy et al., 2008). The formula for calculating the NBR is as follows:

$$NBR = (NIR - SWIR) / (NIR + SWIR) \quad (1)$$

For the identification of burnt pixels, we utilised a threshold value below -0.1. This was determined based on techniques used for the visual interpretation of burn scars in agricultural fields (Schepers et al., 2014). To verify the accuracy of the identified burn areas, we conducted several quality control checks. These checks involved a manual inspection of a sample of the identified burnt areas in the satellite imagery, which were then cross-verified with ground-truth data.

Ambient Air Quality Assessment

The evaluation of the impacts of stubble burning on the ambient air quality involved using air pollution data sourced from the Punjab Pollution Control Board. We focussed primarily on the concentrations of PM2.5 and PM10, which are known to be the significant air pollutants in the region.

Data Cleaning

Before proceeding with the analysis, we first undertook a thorough cleaning of the air pollution data to eliminate outliers. This step was crucial in ensuring the integrity and validity of our analysis. It involved the careful removal of data points that exhibited inconsistency with the overall trends or appeared to be erroneous due to potential data entry errors or system glitches. This meticulous cleaning process was essential to enhance the accuracy of our subsequent air quality distribution map.

Spatial Interpolation

After data cleaning, the next step involved spatial integration of the data. To achieve this, we utilized the ArcGIS spatial join feature. This tool was used to merge the geospatial coordinates of the monitoring station locations with their corresponding pollution values of PM2.5 and PM10. This ensured that each point in our analysis represented a precise geolocation with its corresponding pollution level.

Furthermore, we were also interested in estimating the pollution values for locations that were not directly monitored by the PPCB. To fill these gaps, we utilised a spatial interpolation technique known as Inverse Distance Weighting (IDW). IDW interpolation is a widely adopted method in environmental monitoring that estimates unknown values by averaging the values of known samples, with the weights being the inverse of the distance to the target location. The closer a known sample point is to the target location, the higher the influence it will exert on the estimated value. We maintained a cell size of 10 meters for the interpolation to ensure high-resolution mapping.

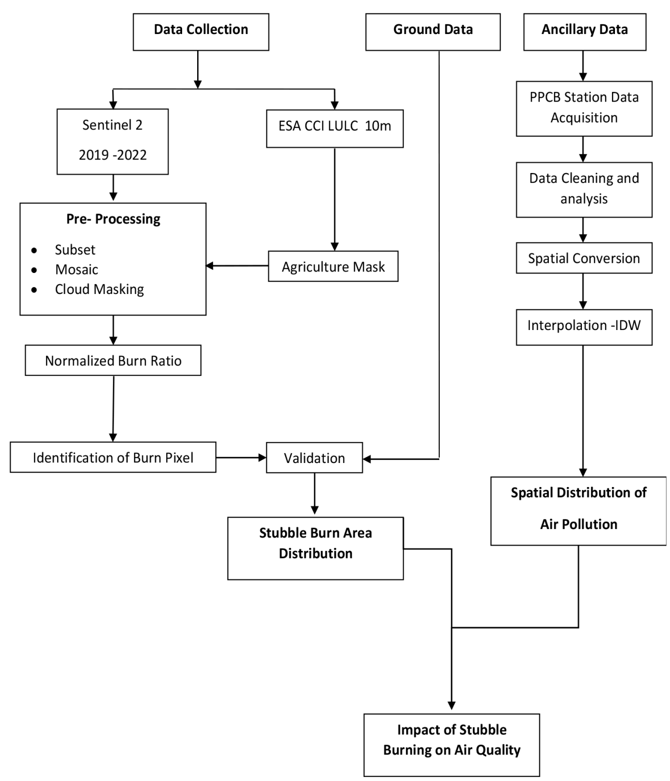

Figure 3: Methodology flow chart.

Resultant Analysis

By integrating the outcomes of the stubble burning monitoring and the ambient air quality assessment, we aimed to gain a comprehensive understanding of how stubble burning might have contributed to air pollution in Punjab during the study period. Additionally, we sought to delineate the potential implications of these contributions for public health and overall environmental quality.

The insights gained from this rigorous methodology will serve as a solid foundation upon which effective management strategies and mitigation measures can be designed. These strategies would aim to not only curb the prevalent practice of stubble burning but also significantly ameliorate the air quality in Punjab, thereby safeguarding human health and the environment.

Results and Discussion

Stubble Burning Monitoring

The analysis of stubble-burning events in Punjab, based on high-resolution Sentinel-2 imagery, revealed significant variations in the burnt area for the months of October and November between 2019 and 2022. The results are described in Table 2, and Figures 4 and 5 show the aerial distribution of stubble burn area from 2019 to 2022. The spatial pattern of stubble burning is shown in Figures 6 (a-d) and 7 (a-d).

The spatial and temporal patterns of stubble burning events from October 2019 to 2022 in Punjab displayed notable variations. Analysis of October's data for the four years exhibited diverse distributions and incidences. In 2019, there were fewer stubble burning instances, mainly confined to the northwestern region. However, October 2020 witnessed a surge in these events, predominantly in the northwestern and eastern regions of Punjab. While the patterns in 2021 and 2022 bore a close resemblance to each other, the majority of the events were concentrated in the northwestern area, suggesting a potential hotspot for stubble burning. Table 2 highlights the fluctuating trends in the October burnt area, peaking at 755.38 sq km in 2020 and dipping to its lowest at 209 sq km in both 2019 and 2021.

Table 2: Burnt area (Sq Km) in Punjab from stubble burning (October and November 2019-2022)

Month	*Year*	*Burnt Area (Km^2)*
October	2019	209
October	2020	755.38
October	2021	209
October	2022	272
November	2019	8307.102
November	2020	10103
November	2021	10315
November	2022	9379

Parallely, we examined the November stubble-burning events from 2019 to 2022. The patterns in November 2019 and 2020 bore a close resemblance to each other, albeit with an increased number of events in 2020. In contrast, November 2021 and 2022 demonstrated an overall escalation in stubble burning, particularly in western Punjab. As displayed in Table 2, the burnt area in November was consistently larger compared to October across all years. The burnt area extended over 8307.102 sq km in November 2019, expanded to 10103 sq km in 2020, peaked at 10315 sq km in 2021, and then contracted slightly to 9379 sq km in 2022.

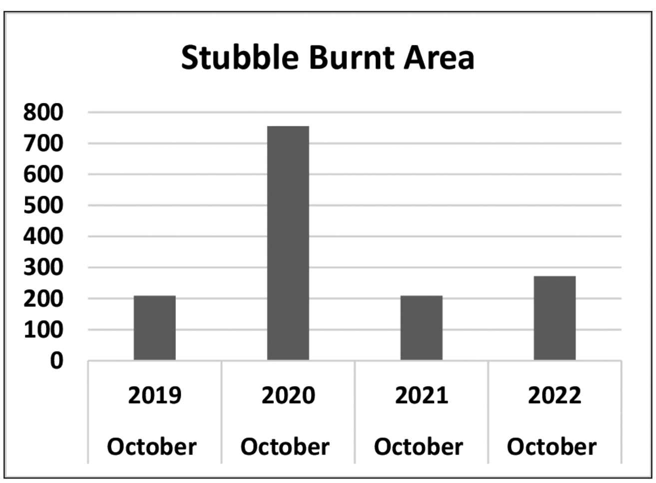

Figure 4: Stubble burning in October.

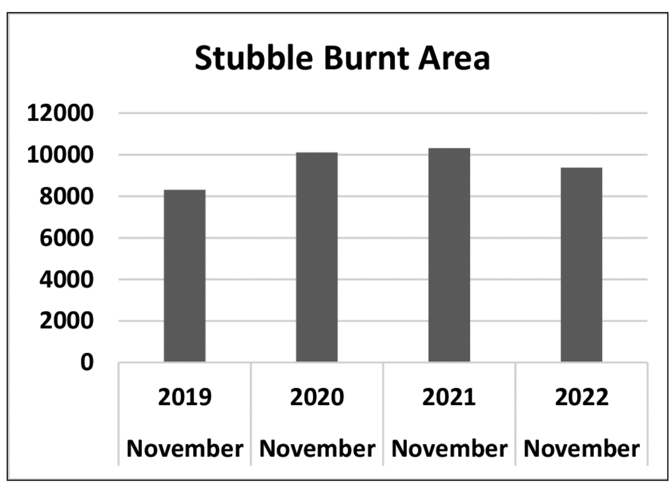

Figure 5: Stubble burning in November.

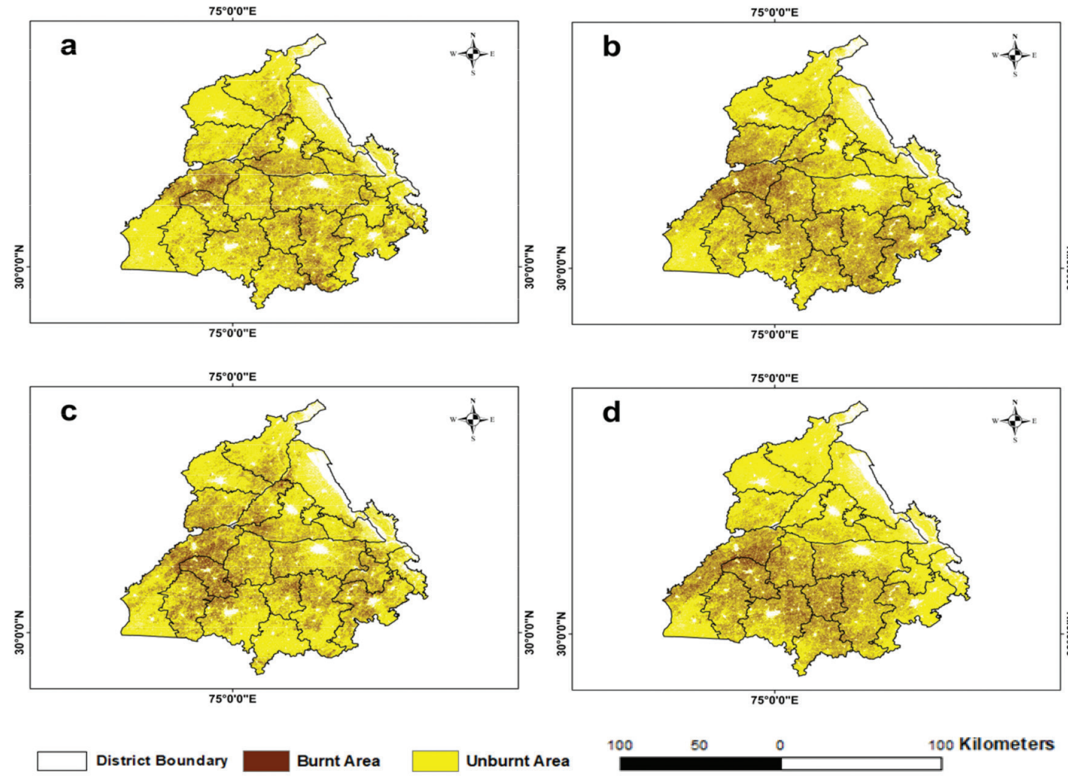

Figure 6 (a-d): Stubble burn area map during October (a) 2019, (b) 2020, (c) 2021 and (d) 2022.

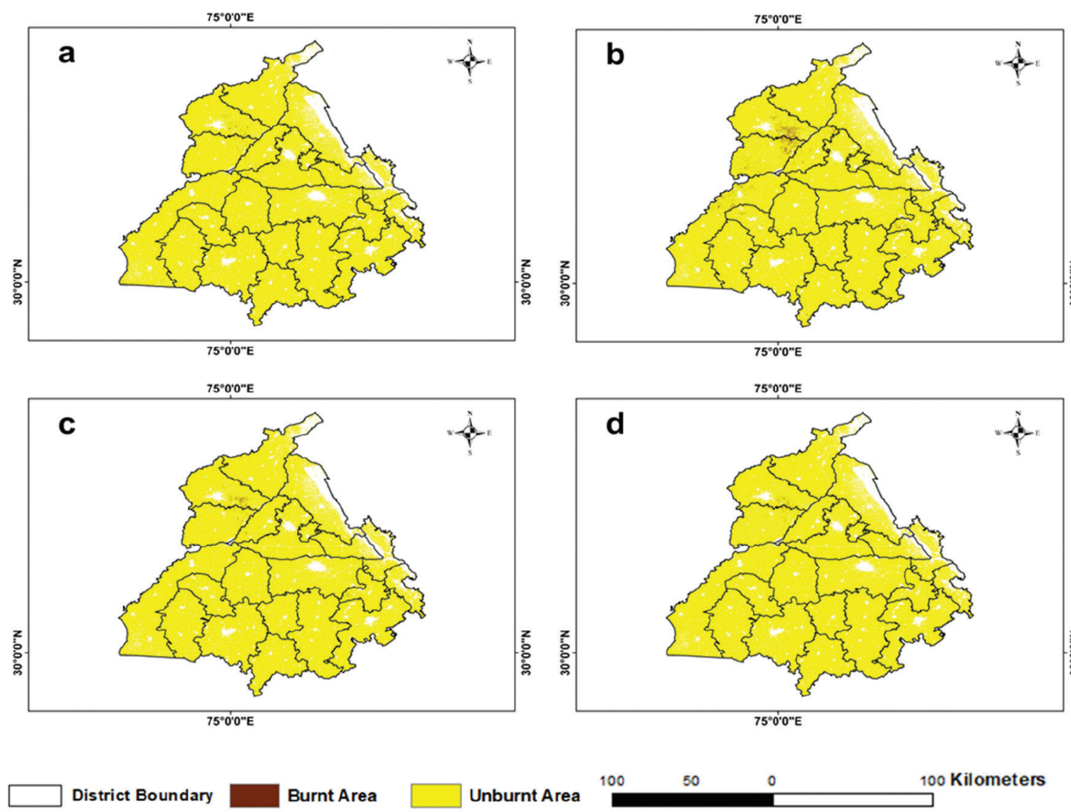

Figure 7 (a-d): Stubble burn area map during November (a) 2019, (b) 2020, (c) 2021 and (d) 2022.

Collectively, our results highlight a trend towards more extensive stubble burning in November as opposed to October across all years investigated. While October's burnt area displayed considerable annual variations, November's burnt area was consistently high, with only marginal year-to-year fluctuations. These findings underscore the recurring issue of stubble burning in Punjab and its potential implications for ambient air quality, particularly in November, which experiences a high intensity of these events.

Accuracy Assessment

To ensure the robustness of our results, we conducted an accuracy assessment using the confusion matrix method. This involved evaluating the effectiveness and quality of the stubble burning detection and monitoring outcomes for the years 2019 to 2022. During the evaluation process, we calculated various measures, including kappa statistics, producer's accuracy (PA), user's accuracy (UA), and overall accuracy (OA), as recommended by standard procedures in remote sensing research (Singh et al., 2009).

Producer's accuracy was determined by dividing the number of correctly identified pixels by the total reference pixels for a given category (Schepers et al., 2014). This measure reflects the model's ability to correctly identify actual instances of stubble burning. User's accuracy, on the other hand, was calculated by dividing the total number of correctly classified items for a specific category by the total number of items that were classified in that category, regardless of their true nature. This measure indicates the likelihood that a pixel classified as a burnt area is indeed burnt. Overall accuracy was calculated by dividing the sum of true positives and true negatives by the total number of instances assessed. This measure provides an aggregate indication of the model's performance. Table 3 presents the accuracy assessment results for the NBR model applied in detecting and monitoring stubble-burning areas over the study period.

Air Quality Assessment

The Central Pollution Control Board's guidelines establish that the maximum permissible hourly and annual concentrations of PM2.5 and PM10 are 40-60 $\mu g/m^3$ and 60-100 $\mu g/m^3$, respectively. Our analysis of ambient air quality in Punjab, concentrating on the months of October and November from 2019 to 2022, and focusing on PM2.5 and PM10 concentrations, uncovers intriguing trends and significant variations, as presented in Figures 8 and Figure 9. Table 4 displays the statistics of the PM2.5 and PM10 during the period.

In October 2019, an examination of the PM2.5 and PM10 levels across the regions in Punjab revealed that the majority of them had concentrations exceeding the permissible limits, with the exception of the northwestern area. Fast-forwarding to October 2020, a decrease in both pollutant levels was observed, barring the eastern region which saw an increase. When considering October 2021, higher levels of PM2.5 and PM10 were detected in the southern region, contrastingly lower concentrations were found in the northern areas. In October 2022, an overall increment in the pollutants' concentrations was observed across most regions, barring the southeast. A scrutiny of the PM2.5 concentrations over these years reveals the lowest value in 2021 (55.79 $\mu g/m^3$) and the highest in 2020 (72.63 $\mu g/m^3$). PM10 demonstrated a parallel trend, reaching its nadir in 2021 (117.75 $\mu g/m^3$) and zenith in 2020 (152.19 $\mu g/m^3$).

Shifting focus to November, 2019, the PM2.5 and PM10 concentrations were generally low across most regions, with the exception of the southeastern area. November 2020 saw a rise in PM2.5 in most areas except the south, while PM10 levels escalated in the eastern region. A year later, in November 2021, the southeast stood out as the only region with high pollutant levels. By November 2022, a general increase in pollutant levels was observed, save for the northwest. Both PM2.5 and PM10 concentrations consistently clocked higher readings in November compared to

Table 3: Accuracy assessment of burned area and unburned area

LULC Classes	*2019*		*2020*		*2021*		*2022*	
	UA (%)	*PA (%)*	*UA (%)*	*PA (%)*	*UA (%)*	*PA (%)*	*UA (%)*	*PA (%)*
Burned-Area	98.21	95	94.44	94.44	84.37	90.75	96.43	83.07
Unburned-Area	83.24	100.00	89.65	100.00	90.49	81.82	85.00	92.31
Overall accuracy (%)	89.63		87.41		89.43		85.73	
Kappa coefficient	0.85		0.68		0.87		0.75	

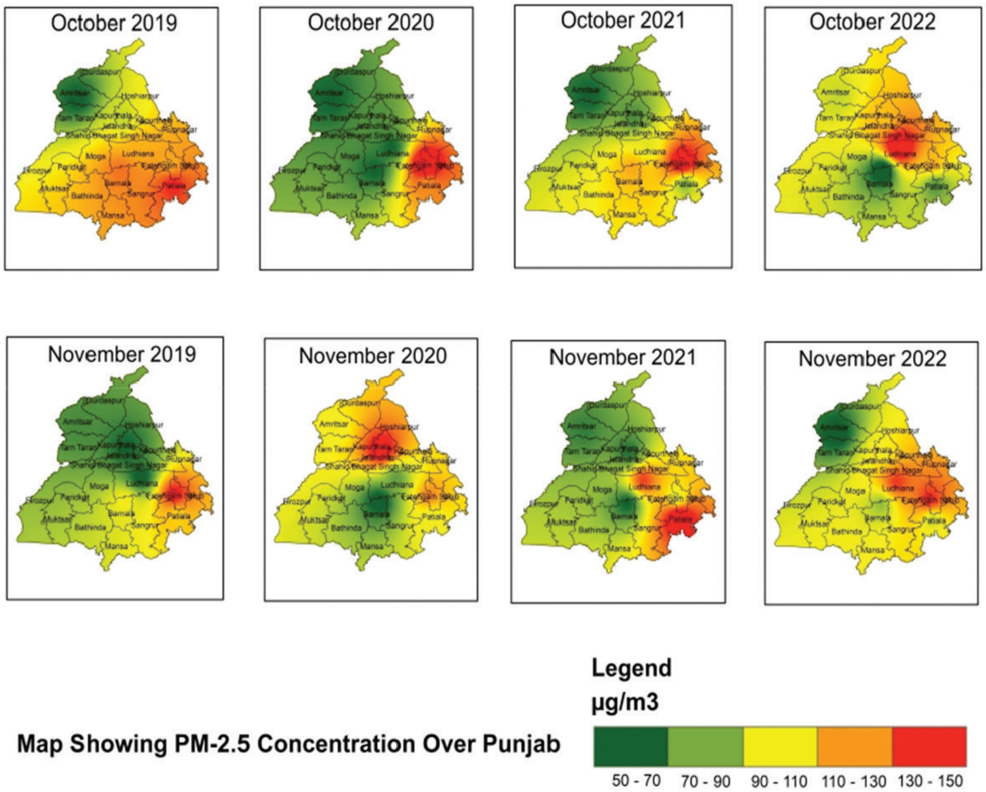

Figure 8: Spatial distribution of air pollution concentration of PM2.5.

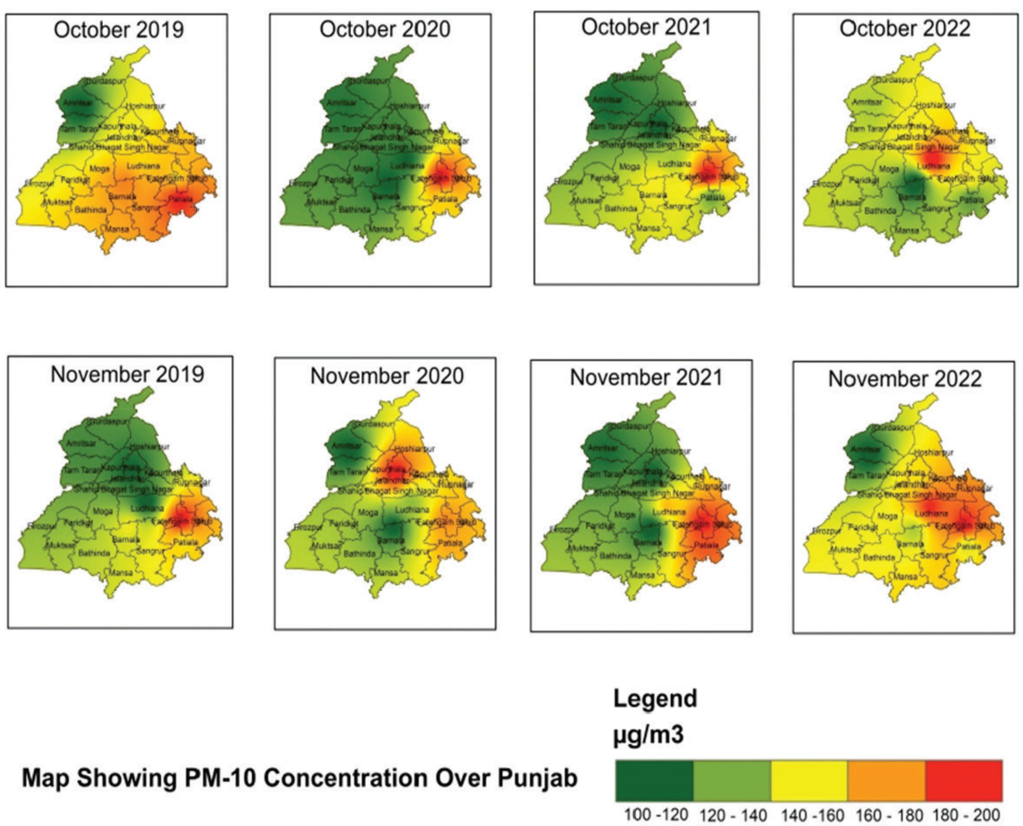

Figure 9: Spatial distribution of air pollution concentration of PM10.

Table 4: PM2.5 and PM10 Concentrations (μg/m³) in Punjab (October and November 2019-2022)

Month	*Year*	*PM2.5*	*PM10*
October	2019	68.73	131.99
October	2020	72.63	152.19
October	2021	55.79	117.75
October	2022	60.17	127.00
November	2019	85.01	175.56
November	2020	92.10	188.09
November	2021	97.33	198.41
November	2022	84.49	165.81

October. The peak values for both pollutants were recorded in 2020 and 2021.

Taking a holistic view, the air quality in Punjab exhibited a consistent decline in November compared to October, with fluctuating yearly concentrations of PM2.5 and PM10. Elevated levels of these particulate matter pose significant health risks, such as respiratory and cardiovascular diseases. In a region like Punjab, where air pollution levels are concerning, these risks underscore the urgent need for effective measures to alleviate air pollution.

Relationship Between Stubble Burnt Area and Air Pollution Concentration

The comparative analysis of the burnt areas from stubble-burning events and ambient air quality in Punjab during the months of October and November from 2019 to 2022 unveils noteworthy trends and correlations. Stubble burning was found to be more widespread in November than in October, although with slight annual fluctuations. Similarly, the air quality, as indicated by PM2.5 and PM10 concentrations, was consistently worse in November compared to October for all the years analysed. These trends suggest a potential link between the prevalence of stubble burning and the deterioration of ambient air quality in Punjab during these months.

To statistically test this relationship, we calculated the Pearson correlation coefficients between burnt areas and PM2.5 and PM10 concentrations for both October and November combined over the four-year period shown in Figure 10 for PM10 and Figure 11 for PM2.5. The findings expose a robust positive correlation between the burnt area and both PM2.5 (0.8629) and PM10 (0.8481) concentrations. This suggests that an escalation in stubble burning events directly contributes to a considerable increase in air pollution levels during both October and November. The strong correlation for both PM2.5 and PM10 concentrations reaffirms the considerable impact of stubble burning events on the degradation of Punjab's ambient air quality.

These findings emphasise the need for effective monitoring and mitigation strategies to reduce the impact of stubble burning on air quality and public health in the region. Further research could explore the effects of meteorological factors on the dispersion of pollutants and examine the health impacts associated with the observed air pollution levels. Additionally, expanding the analysis to include other pollutants, such as CO, NOx, and VOCs, could provide a more comprehensive understanding of the relationship between stubble burning and air quality.

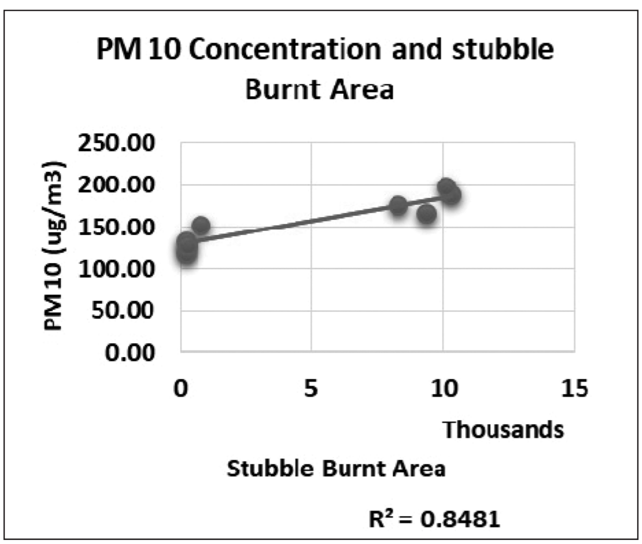

Figure 10: Scatter Plot Graph (PM10 vs Stubble Burn area).

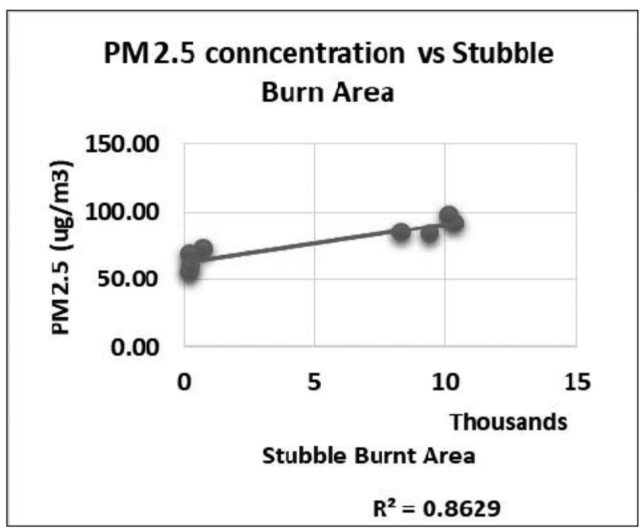

Figure 11: Scatter Plot Graph (PM2.5 vs Stubble Burn area).

Conclusion

This study provides a comprehensive view of the spatial and temporal patterns of stubble burning events in Punjab, along with their potential impact on air quality, particularly during October and November. The results confirm a significant correlation between the extent of stubble burning and escalating air pollution levels, especially in November when both burnt areas and air pollution concentrations are consistently higher. However, some deviations between the burnt area and air pollution levels in certain years point towards the complex dynamics of this relationship, implicating other factors, such as meteorological conditions and emissions from various sources, as potential determinants of air quality. The study underlines the urgency for effective management and mitigation strategies to combat the deleterious impacts of stubble burning on air quality and public health in Punjab. Strategies could include promoting alternative farming practices like incorporating crop residues into the soil or using residue management machinery. These measures could help alleviate the reliance on stubble burning and contribute to improving air quality in the region. Policymakers' role in implementing strict regulations and enforcement measures can dissuade stubble burning practices and encourage the adoption of sustainable agricultural methods. Future research should aim at establishing a causal relationship between stubble burning and air pollution, incorporating data from other pollution sources and meteorological variables to better understand the multitude of factors impacting air quality in Punjab.

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