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Spatio-temporal variability in fire events due to crop residue burning and their impact on atmospheric variables using ground and remote sensing data in Punjab

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सार – हमने 375 मीटर की दूरी पर स्थित विजिबल इन्फ्रारेड इमेजिंग रेडियोमीटर सुइट (VIIRS) से 2017-2021 की गेहूं और चावल की कटाई की अवधि के दौरान पंजाब में सक्रिय आग की घटनाओं की निगरानी और मानचित्रण करने का प्रयास किया। विश्लेषण से पता चला कि सभी वर्षों के दौरान पंजाब के मध्य क्षेत्र में आग लगने की सबसे अधिक घटनाएं देखी गईं, उसके बाद दक्षिण-पश्चिम क्षेत्र में तथा सबसे कम घटनाएं उत्तर-पूर्वी क्षेत्र में देखी गईं। इसके अलावा, गेहूं की फसल के दौरान, 2019 में आग की सबसे अधिक घटनाएं देखी गईं, जो उत्तर-पूर्व, मध्य और दक्षिण-पश्चिम क्षेत्रों में क्रमशः 2535, 11062 और 6212 थीं। हालांकि, चावल की फसल के दौरान, 2020 में उत्तर-पूर्व में सबसे अधिक 2857 आग की घटनाएं और 2021 में मध्य और दक्षिण-पश्चिम क्षेत्रों में क्रमशः 40960 और 30351 देखी गईं। आग की घटनाओं की संख्या के अनुरूप, केंद्रीय प्रदूषण नियंत्रण बोर्ड (CPCB) से प्राप्त आंकड़ों के अनुसार, गैसों और कणिका तत्वों की उच्चतम सांद्रता भी मध्य क्षेत्र में देखी गई। गेहूं की कटाई के मौसम के दौरान, मध्य क्षेत्र में मई 2018 में $PM_{2.5}$ और PM_{10} की उच्चतम सांद्रता और मई 2019 में SO_2 और O_3 की उच्चतम सांद्रता देखी गई। इसी प्रकार, चावल की कटाई के मौसम के दौरान, मध्य क्षेत्र में नवंबर 2017 में $PM_{2.5}$ और PM_{10} की उच्चतम सांद्रता और 2018 में SO_2 की उच्चतम सांद्रता देखी गई। हालाँकि, मध्य क्षेत्र में NO_2 की उच्चतम सांद्रता अक्टूबर 2018 में और O_3 की उच्चतम सांद्रता अक्टूबर 2020 में देखी गई। Soumi-NPP उपग्रह से प्राप्त NO_2 और SO_2 की सांद्रता के विश्लेषण के परिणाम भी CPCB के समान ही थे। गैसों और कण पदार्थों की इतनी अधिक सांद्रता का कारण फसल अवशेष जलाना हो सकता है; आग की संख्या और कण पदार्थों ($PM_{2.5}$ और PM_{10}) की सांद्रता के बीच महत्वपूर्ण सकारात्मक सहसंबंध देखा गया। वायु गुणवत्ता में खतरनाक गिरावट को देखते हुए, किसानों को प्रोत्साहन और व्यवहार्य विकल्प प्रदान करके इस क्षेत्र में इस प्रथा पर रोक लगाने की प्रत्यक्ष आवश्यकता है।

ABSTRACT. We attempted monitoring and mapping of the active fire events in Punjab, during the wheat and rice harvesting period of 2017-2021 from the Visible Infrared Imaging Radiometer Suite (VIIRS) at 375 m aboard. The analysis showed that the highest fire counts were observed in the central region, followed by the south-west and the lowest in the north-east region of Punjab during all the years. Moreover, during the wheat season, highest fire counts were observed in 2019, being 2535, 11062 and 6212 in north-east, central and south-west regions, respectively. However, during rice, highest fire counts were observed in 2020 in the north-east being 2857 and in 2021 the central and south-west regions being 40960 and 30351 respectively. In line with the number of fire counts, the highest concentration of gases and particulate matter obtained from the Central Pollution Control Board (CPCB) was also observed in the central zone. During the wheat harvesting season, central zone experienced the highest concentration of $PM_{2.5}$ and PM_{10} in May 2018 and that of SO_2 and O_3 in May 2019. Similarly, during the rice harvesting season, central zone also experienced the highest concentration of $PM_{2.5}$ and PM_{10} during November 2017 and that of SO_2 in 2018. However, the highest concentration of NO_2 was observed in October 2018 and that of O_3 in October 2020 in the central region. Analysis of the concentration of NO_2 and SO_2 obtained from the Soumi-NPP satellite also had similar results to CPCB. Such a high concentration of gases and particulate matter might be attributed to crop residue burning a significant positive correlation was observed between fire counts and concentration of particulate matter ($PM_{2.5}$ and PM_{10}). In view of the alarming deterioration of air quality, there is a dire need to check this practice in the region by providing incentives and viable alternatives to the farmers.

Key words – Crop residue burning, Environmental, Implications, Satellite, Remote sensing.

1. Introduction

Crop residue burning is one of the major concerns that imposes a potential threat to our ecosystem (Kingra *et al*., 2021). It causes a rise in the emissions of greenhouse gases and particulate matter, which exposes people to health risks along with depletion of soil nutrients. Burning crop residue makes a significant contribution to air pollution. Rice, wheat, maize and sugarcane make up the majority of the numerous crops that contribute to our nation's overall PM_{10} emissions, at roughly 90%. According to Sahu *et al.*, 2021, annual emissions for $PM_{2.5}$, PM_{10}, BC and OC, CO, NO_x, SO_2, VOC, CH_4 and CO_2 were estimated to be 990.68 Gg/yr, 1231.26 Gg/yr, 123.33 Gg/yr, 410.99 Gg/yr, 11208.18 Gg/yr, 484.55 Gg/yr, 144.66 Gg/yr, 1282.95 Gg/yr, 785.56 Gg/yr and 262051.06 Gg/yr, respectively. Air pollution has been a potential threat to life on earth as it is significantly increasing health issues. It also leads to increased diseases all over the world with severe impacts on developing countries (Cohen *et al*., 2015). The problem of air pollution is further aggravated significantly, especially in north-west India, as a result of crop residue burning during the harvesting season. Zhuang *et al.*, 2018 reported that short term variations in particulate matter concentrations are more strongly affected by intense crop burning than in the long term.

About one fifth to one fourth of the biomass residue is burnt by farmers in open fields in India (Ravindra *et al.*, 2019a, 2019b). Biomass burning is also leading to excessive depletion of our major natural resources. Due to the practice of increased mechanization in the Indo-Gangetic Plains (IGP), a huge amount of crop residue is left after harvest, which cannot decompose quickly. According to "The Punjab Preservation of Sub-soil Water Act-2009" farmers cannot go for rice transplanting before June 15th, as a result, harvesting of rice in Punjab gets extended up to mid-November. Hence, farmers are left with no option other than burn to the residue to go for sowing of wheat in time. This leads to increased air pollution and environmental degradation, especially during the months of October and November in north-west India.

Satellite data has been used to monitor biomass burning at a regional to global scale using algorithms that detect the location of active fire at the time of satellite overpass and the burnt area mapping algorithms that map directly the spatial extent of the areas affected by fire (Kingra *et al.*, 2021). The NASA Moderate Resolution Imaging Spectro-radiometer (MODIS) on the Terra and Aqua satellites has specific features for fire monitoring and has been used to systematically generate global MODIS land products (Justice *et al*., 2006). Nair *et al*., (2020) analyzed the contribution of stubble burning to air quality of Delhi during October and November 2017. Yang *et al*., 2020 analyzed the satellite and ground observations and developed a regional air quality modeling system to estimate the contribution of open biomass burning to surface $PM_{2.5}$ concentration during a severe haze episode.

In order to assess the area affected due to burning and its climatic and environmental implications, proper monitoring through satellite data with mapping algorithms, remote sensing techniques as well as statistical analysis is needed. Geostationary Satellites such as INSAT-3D/3DR having modest resolution and hyper temporal capability are being used for identifying large fires. Algorithms have been developed for detection of active fire events such as multi-channel contextual algorithm (Singh, 2018). To monitor fire events, satellites such as the Terra and Aqua NASA Moderate Resolution Imaging Spectro-radiometer (MODIS) have been used to assess the day and extent of burning at 500 m resolution (Justice *et al*., 2002 and Roy *et al*., 2005). Chhabbra *et al.* (2019), reported a notable increase in the number of fire incidents in Punjab's southwest and eastern regions. Results indicated that the burning events in November 30, 2018, account for 85% of the events found in 2017 and roughly 59.10% of the events found in 2016. It suggests that a number of state and federal government initiatives have greatly decreased the amount of rice stubble burned over the years.

As crop residue burning has severe climatic and environmental implications, therefore, it is necessary to assess and map the area which is under the effect of stubble burning so that its impact can be investigated more efficiently. As the north-west Indian region suffers from its severe implications every year during the crop harvesting season, thus, keeping this in view, this research investigation was planned to assess the climatic and environmental implications of crop residue burning in Punjab using ground observations and satellite remote sensing.

2. Materials and methods

2.1. *Study area*

The state of Punjab is situated in the north-west region of India with a total geographical area of 50,362 km². The Latitudinal range of the state extends from 29º 30´ to 32º 32´ north and the longitudinal range from 73º 55´ to 76º 50´ east. It comprises of 23 districts which are subdivided into 93 Tehsils. In this investigation, the whole state was divided into the following three agroclimatic regions (Fig. 1):

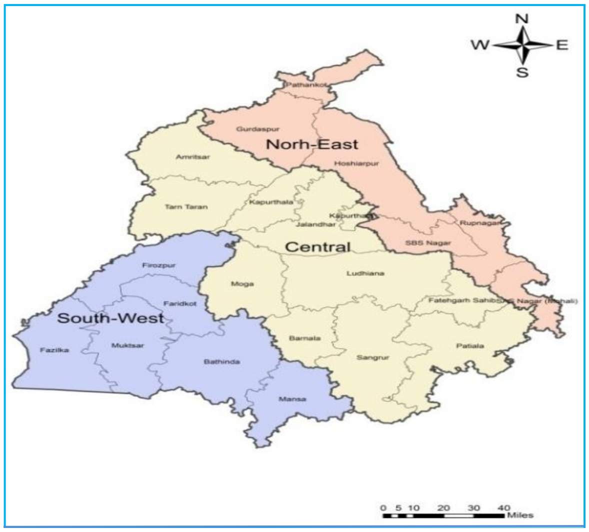


Fig. 1. Map of Study area.

(i) The North-East region comprises of Pathankot, Gurdaspur, Hoshiarpur, Rupnagar, SAS Nagar and SBS Nagar districts.

(ii) The Central region comprises of Amritsar, Kapurthala, Tarn-Taran, Jalandhar, Barnala, Moga, Ludhiana, Fatehgarh Sahib, Sangrur, Malerkotla and Patiala districts.

(iii) The South-West region comprises Faridkot, Firozpur, Mansa, Bathinda, Sri Muktsar Sahib and Fazalika districts.

2.2. *Data collection / downloading*

2.2.1. *Fire counts*

To assess fire counts of Punjab on a real time basis, data of SUOMI-VIIRS (375 m) was downloaded from https://firms.modaps.eosdis.nasa.gov/download/ the years 2017-2021 during wheat (March-May) and rice harvesting season (September-November). The satellite data on fire counts of Punjab state was further sub-categorized for three agroclimatic regions of the state using Arc-GIS software.

2.2.2. *Concentration of gases and particulate matter*

Data on the concentration of particulate matter gases namely $PM_{2.5}$, PM_{10}, SO_2, NO_2 and O_3 for various districts of Punjab was obtained from the website of the Central Pollution Control Board (CPCB) (https://cpcb.nic.in/) for wheat (March-May) and rice harvesting season (September-November) from 2017-2021. Data on tropospheric concentration of gases (NO_2 and SO_2) for the same period was obtained over the Punjab area from Sentinel -5P (extracted through Google Earth Engine).

2.3. *Statistical analysis*

Data on fire counts, concentration of particulate matter and gases as well as weather variables for the wheat and rice harvesting period during 2017-2021 was analysed and compared to detect deviations and variability due to residue burning events by using standard statistical procedures such as mean, standard deviation, correlation *etc*. Correlation of fire events was studied with concentration of particulate matter and gases as well as weather variables to assess the environmental and climatic implications of residue burning in Punjab during the wheat and rice harvesting season by using the following standard statistical measures:

Spearman's rank correlation measures the strength and direction of association between two ranked variables. It basically gives the measure of monotonicity of the relation between two variables *i.e.* how well the relationship between two variables could be represented using a monotonic function. Significance of correlation was checked at 5% level. The formula used for Spearman's rank correlation is as following:

$$\rho = 1 - \frac{6 - \sum di^2}{n(n^2 - 1)}$$

3. Results and discussion

3.1. *Spatio-temporal variability in fire counts*

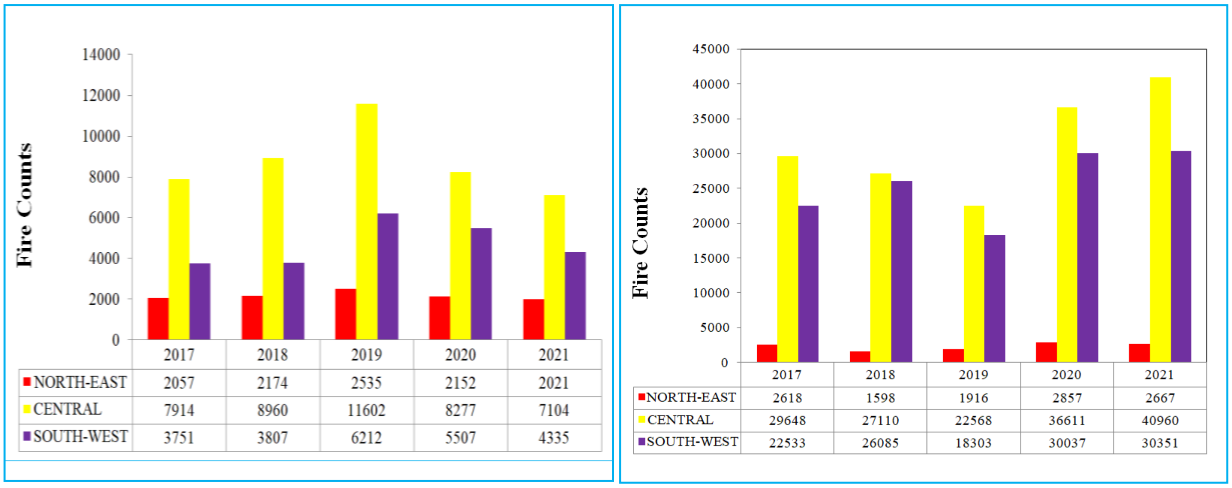
3.1.1. *Wheat harvesting season*

(i) Analysis of Zones: Year wise

During the wheat harvesting period, highest fire counts were observed in 2019 in all the agroclimatic regions, of Punjab, being 2535, 11602 and 6212 in the north-east, central and south-west region, respectively (Figs. 2 and 3). In general, the fire counts increased from 2017 to 2019, but started to decrease thereafter *i.e*. in 2020 and 2021. It was observed that the maximum increase *w.r.t.* The previous year was observed in 2019 in all the three regions, being 16.60 %, 29.4 % and 39.9 % for north-east, central and south-west region, respectively, and then again slightly decreased to only 2021, 7104 and 4335, which is a decrease of 6.08 %, 14.17 % and 21.28 % in north-east, central and south-east region respectively. This could be due to the strict policy measures taken by the government and also due to the awareness among farmers about the use of wheat straw as animal feed and other purposes.

(ii) Analysis of districts: month wise

It was observed that, for all the years, the maximum fire counts were found in the month of May for all the



Figs. 2 (a&b). Variation in fire counts during a) wheat and b) rice harvesting season of 2017- 2021 in different agroclimatic regions of Punjab.

districts, which signifies high burning of residue in the month of May. Also, they were significantly higher as compared to the months of March and April as in May harvesting is generally completed and burning starts.

In the North East zone, Gurdaspur district had highest burning events. Among all the years they were highest in 2019 (1223). While in the Central Zone (which is also largest in area), burning events were found to be maximum in different districts for different years. For the years 2017 and 2021, Tarn-Taran was found to have the highest number of fire counts, being 1620 and 1101 respectively, while for the years 2018 and 2019 Amritsar was found to have the highest no of fire counts being 1467 and 1684 respectively. Among all the years the highest number of fire counts were found in the year 2019, in Ludhiana district, count being 1791. In the South-West zone, the highest number of fire counts were observed to be in Firozpur district. The highest fire counts were observed in the year 2019, count being 1456 (Table 4).

So it can be concluded that although the burning increased from 2017 to 2019, after 2019 (*i.e.* in 2020 and 2021), it decreased due to stricter government policies, better adaptation of management practices by farmers and follow up of precautionary measures by farmers during and after the lockdown in 2020 and 2021.

(iii) Analysis of zones: month wise

It can be clearly observed that for all the regions, from 2017-2021, fire counts are minimal in the month of march, increase in April and reach their maximum value in the Month of May as burning activities increase significantly after the harvest of wheat.

Among all the zones, highest fire counts were found in the year 2019 being 2535, 11602 and 6212 for North-East, Central and South-West zone respectively. Among all the zones, Central zone was observed to have highest fire counts owing to the largest area, while minimum counts were found in the North East region (being smallest in area). Burning was found to increase from 2017 to 2019 for all the years, highest increase being found in 2018 in the South-West Zone (39.97% *i.e* from 4438 in 2018 to 6212 in 2019). It was found to decrease in 2020 and 2021, owing to lockdown regulations and stricter government policies (Table 4).

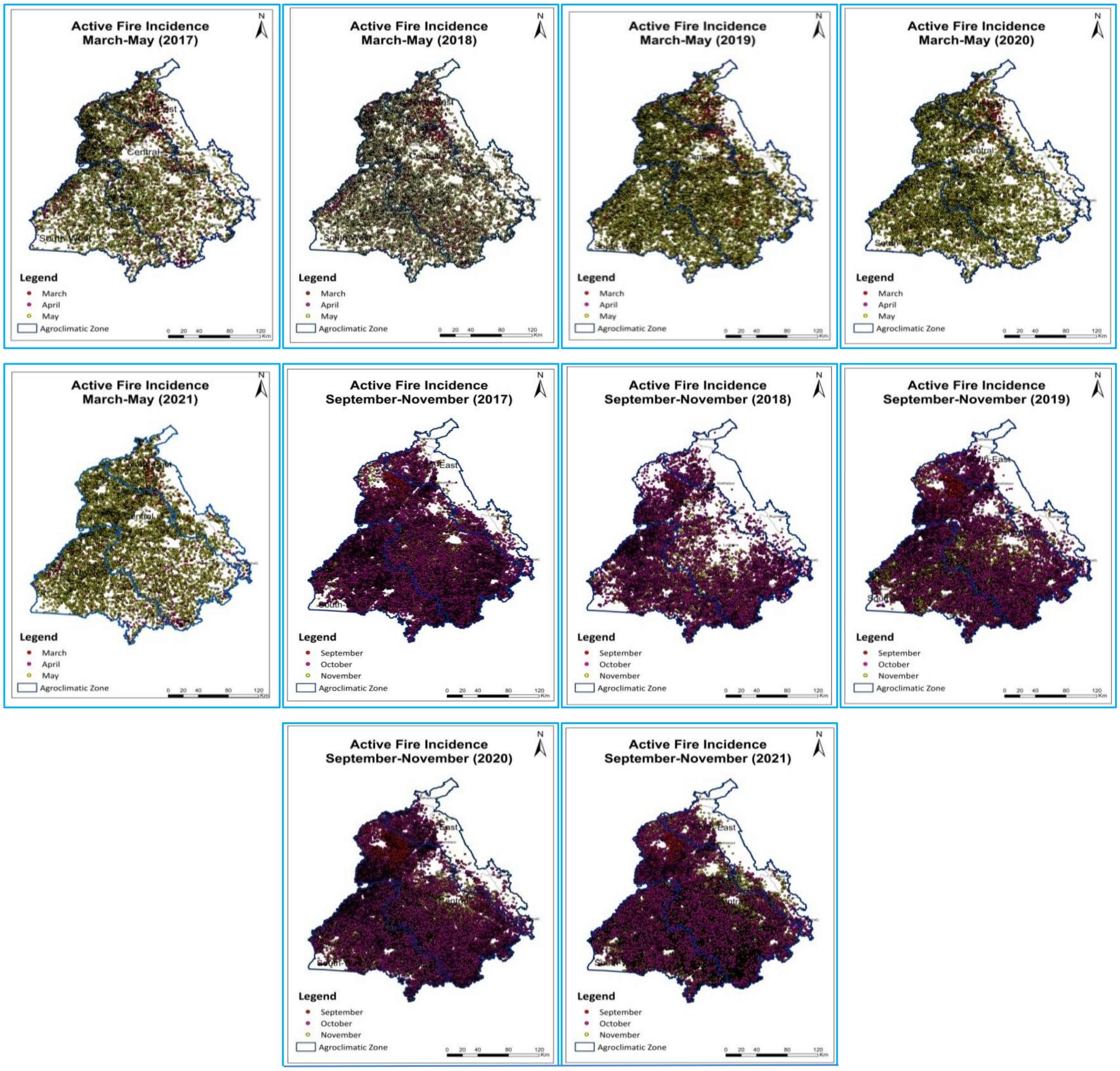
3.1.2. Rice harvesting season

(i) Analysis of zones: year wise

During the rice harvesting season, central and south-west regions observed the highest fire counts in 2021 (40960 and 30351) and lowest in 2019 (22568 and 18303), whereas the north-east region observed highest count (2857) in 2020 and lowest (1598) in 2018. It was observed that the maximum increase in fire counts *w.r.t.* previous years were observed in 2020, being 49.11%, 62.22% and 64.10% for north-east, central and south-west regions, respectively. As the fire counts for the whole period (day and night) were derived through satellite remote sensing, thus, the study clearly depicted the role of this technology in monitoring fire events. Wang *et al.* (2018) also suggested that remote sensing provides particularly important data for assessing fire events (Figs. 2 and 3).

(ii) Analysis of districts: month wise

It was observed that, burning activities were found to be minimum in the month of September and then increased in October and November. This is because an ordinance was issued in 2008 that made it mandatory for the farmers not to seed rice nursery before 10th May and


Active Fire Incidence March-May (2017)

Active Fire Incidence March-May (2018)

Active Fire Incidence March-May (2019)

Active Fire Incidence March-May (2020)

Active Fire Incidence March-May (2021)

Active Fire Incidence September-November (2017)

Active Fire Incidence September-November (2018)

Active Fire Incidence September-November (2019)

Active Fire Incidence September-November (2020)

Active Fire Incidence September-November (2021)

Fig. 3. Variation in fire counts during wheat (above) and rice (below) harvesting season of 2017- 2021 in different agroclimatic regions of Punjab.

not to transplant before 10th June, which was later converted into a water saving regulation: 'The Punjab Preservation of Sub-soil Water Act' in 2009. Thus this leads to late sowing and hence late harvesting. Hence harvesting generally ends by late October or Early November. This leads to the burning activities to be started in Late October or Early November.

In the North-East zone, similar results were observed in the rice harvesting season. So for all the years, Gurdaspur district was observed to have highest burning events, but contrary to the wheat harvesting season, they were observed to be highest in year 2021 (1425). In the Central zone, the trend was found to be very consistent as for all the years, Sangrur was found to have highest number of fire counts and among all the years the counts were observed to be highest in 2020 (being 9157). Similarly for the South-West zone, the trend was found to be very consistent as for all the years, as Bathinda was found to have highest number of fire counts and among all the years the counts were observed to be highest in 2021 (being 7630) (Table 5).

(iii) Analysis of zones : month wise

In the rice harvesting season as like in the wheat harvesting season fire counts were found to be maximum in Central zone and minimum in the North-East zone. However, trend was found to be variable from 2017 to 2019 in all three zones. For example in 2018 (as compared to 2017), decrease in fire counts was found in the North-East zone and Central Zone, however increase was found in the South-West zone. Maximum decrease (38.96%, *i.e.* from 2618 in 2017 to 1598 in 2018) was found in North-East zone. Conversely in 2019 (as compared to 2018), fire counts increased in North-East region, but decreased in the Central and South-West Zone. In the year 2020, significant increase was observed among all the three zones, also highest increase (64.10% *i.e.* from 18303 in 2019 to 30037 in 2020) was found in the South-west zone. Maximum fire counts were observed in the year 2021 in the Central Zone, fire count being 40960 (Table 5). This could be attributed to the opening of lockdown regulations which allowed all farming activities to be done at ease.

3.2. *Spatio-temporal variability in the concentration of NO_2 obtained from satellite data*

In the wheat harvesting season**,** between 25-28 April 2019, the concentration of NO_2 was found to be 6.95 x 10^{-5} mol/m² in most of the regions of Punjab, but in some districts such as Ludhiana and Mansa it ranged between 6.95 x 10^{-5} to 1.03 x 10^{-4} mol/m² and even exceeded this range in parts of south-west region, which might be attributed due to increase in fire counts as in central region. Between 08-11 May 2019, concentration was minimial in the north east region, except in Gurdaspur and Hoshiarpur where it was found to be in the range of 6.95 x 10^{-5} to 1.03 x 10^{-4} mol/m^2. A similar trend was found in the south-west region and in the central region, the concentration of NO_2 exceeded 1.71 x 10^{-4} mol/m² in some parts and was found to be maximum in the southern part of central region in the period of 18-21 May 2019 (Fig. 4). However, due to fewer gas emissions during lockdown, NO_2 concentration was determined to be quite low in the year 2020. In the period from 17 to 20 May 2020, most of the south-west and north-east regions had NO_2 concentrations below 6.95 x 10^{-5} mol/m², but the majority of the central area displayed concentrations that were dispersedly between 6.95 x 10^{-5} and 1.03 x 10^{-4} mol/m² and even exceeded in some parts (Fig. 4). So it can be clearly seen that the maximum concentration was found in the central zone where burning activity is higher. During 2021, concentration was found to be very low between 23-26 April 2021, which could be due to the reason that activity of burning, had not started till then. Between 01-05 May 2021, concentration has increased moderately and reached a maximum between 07-10 May 2021 in most of the areas, with a major increase in Amritsar and Tarn-Taran exceeding (1.71 x 10^{-4} mol/m²) (Fig. 4). This could be attributed to the increase from burning emissions during the same period.

In the rice harvesting season, during 05-08 October 2018 the concentration of NO_2 was minimial (< 6.95 x 10^{-5} mol/m²) in major parts of the state, however, during 25-28 October 2018 the concentration increased slightly in a very scattered manner in Amritsar, Tarn Taran and Mansa. Between 06-09 November, concentration drastically increased in some parts of the Central region, as in Sangrur, Patiala, Barnala and in the South-West region in Bathinda and Mansa (1.03 x 10^{-4}-1.37 x 10^{-4} mol/m²) (Fig. 7). A Similar trend was observed during the year 2019 (Fig. 5), as the concentration of NO_2 increased from October to November, especially in the central zone of Punjab where burning activity was higher. However, in the year 2020 (Fig. 6), comparatively lower concentration was observed than 2018 and 2019, which could be as a result of lockdown. In 2021 (Fig. 6), concentration of NO_2 increased drastically increased from October-November. Initially, between 06-09 October 2021, most of the Punjab showed NO_2 concentration < 6.95 x 10^{-5} mol/m². However, between 27-30 October 2021, it also rose to 1.03 x 10^{-4} mol/m² in some parts of the south-west region, which could be due to the highest fire counts in the region and between 04-07 November 2021, the concentration of NO_2 even exceeded 1.71 x 10^{-4} mol/m² in some parts of the central region. It is observed that emissions were more in the year 2018 and 2021 as compared to 2019, 2020 and in both the years diwali festival coincided (7th November 2018 and 4th November 2021) with the burning period, which could have contributed to the emissions (Fig. 6).

3.3. *Spatio-temporal variability in the concentration of SO_2 using remote sensing*

In the wheat harvesting season, it was observed that the concentration of SO_2 rose to a maximum in parts of the south-west region in 2019 (Fig. 7). While in 2020, it was more in the north-east region. The range was also much higher in 2019 (1.71 x 10^{-4} mol/m²) than in 2020 (1.03 x 10^{-4} mol/m²) (Fig 7). Lower concentration of SO_2 during 2020 might be attributed to the lockdown conditions. In 2021, the concentration increased significantly, exceeding > 2.0 x 10^{-3} mol/m² between 23-26 April 2021. Concentration of SO_2 during 2020 was lower than 2021, which might be attributed to the lockdown conditions (Fig. 7).

In the rice harvesting season, maximum concentration of gases was found in the central region between 04-07 November 2019 (Fig. 8). In the north-east and central region, concentration of SO_2 was found to be comparatively low whereas it was higher in 2018. In 2020, higher concentrations were found in parts of the central region in the period of 15-18 October 2020, when fire counts comparatively increased Much lower concentrations were found, as it is influenced by other sources also (Fig. 8). In 2021, maximum concentration was

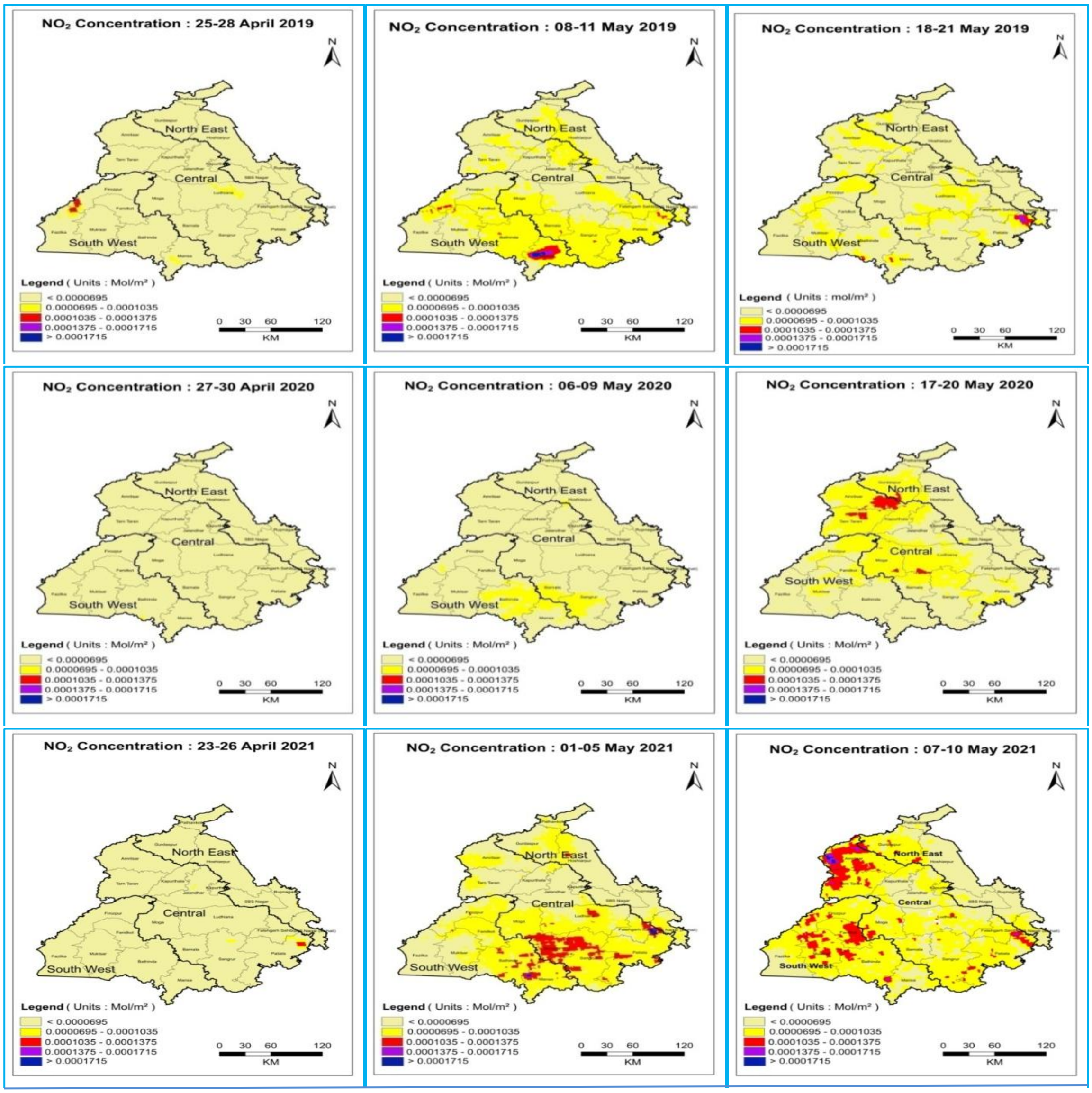


Fig. 4. Spatio-temporal variability in the concentration of NO_2 in Punjab during wheat harvesting period of 2019-21.

found among all the years. Between 04-07 November 2021, especially in the central region, concentration of SO_2 even exceeded 1.71 x 10^{-4} in parts of the central region, which could be due to both high fire counts and diwali the festival. Similar results were observed by Le *et al.* (2020) also reported satellite data to be of great potential for estimating emissions from rice uplands and observed that 3.24 Mt of burnt rice straw produced 583 tonnes of SO_2. Emissions were lower in the south-west region and lowest in the north-east region as these regions experienced much lower fire counts (Fig. 8).

3.4. *Spatio-temporal variability in the concentration of aerosols and gases using ground observations*

3.4.1. *Wheat harvesting season*

The analysis of the concentration of gases and aerosols for the north-east region indicated that pollutants were found to increase substantially in May, which could be attributed to the increase in fire counts during that period. Analysis showed that $PM_{2.5}$ was the highest in May during all the years. And among the years it peaked in May 2019 (72.08 g/m^3), which exceeded both annual and daily recommended standards (Fig. 12), however, it was found to be lowest in April 2020 (25.13 g/m^3), which was under the limit (Fig. 12), which could be as a result of lockdown (Fig. 9). For PM_{10} also similar trend was observed. For SO_2, increase in concentration was observed from 2019-20 for March, April and May but varied

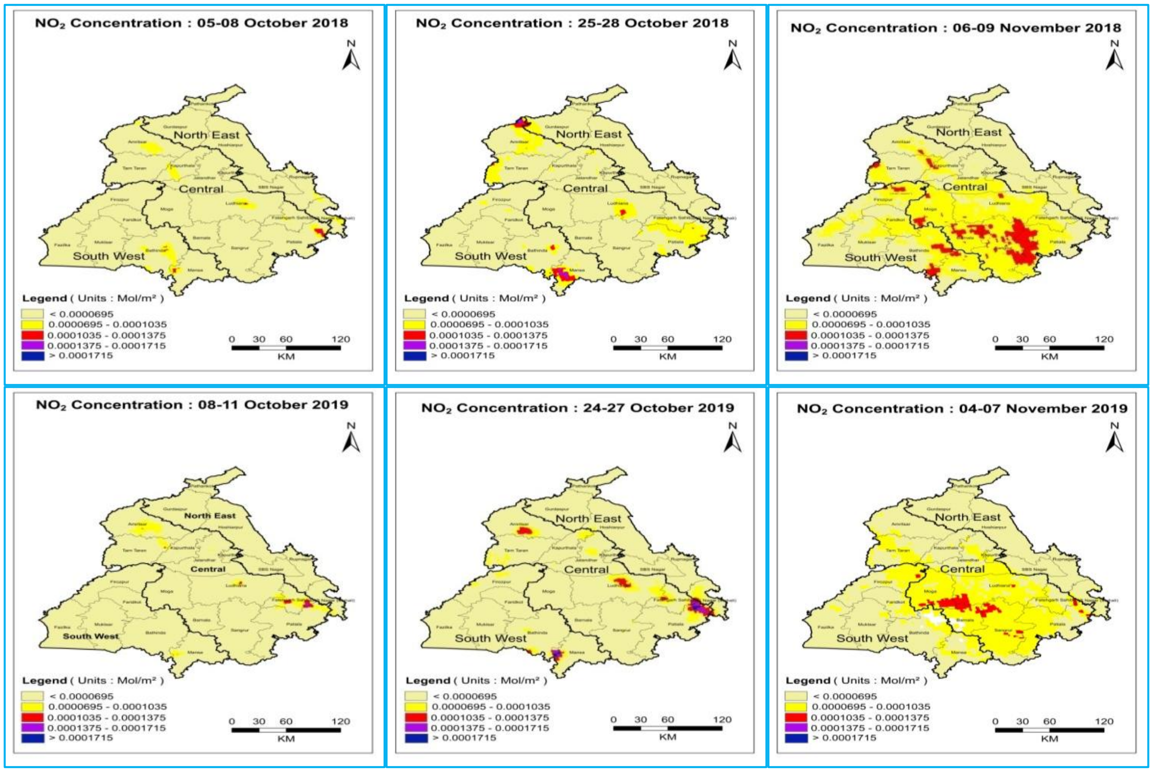


Fig. 5. Spatio-temporal variability in the concentration of NO_2 in Punjab during the rice harvesting period of 2018-19.

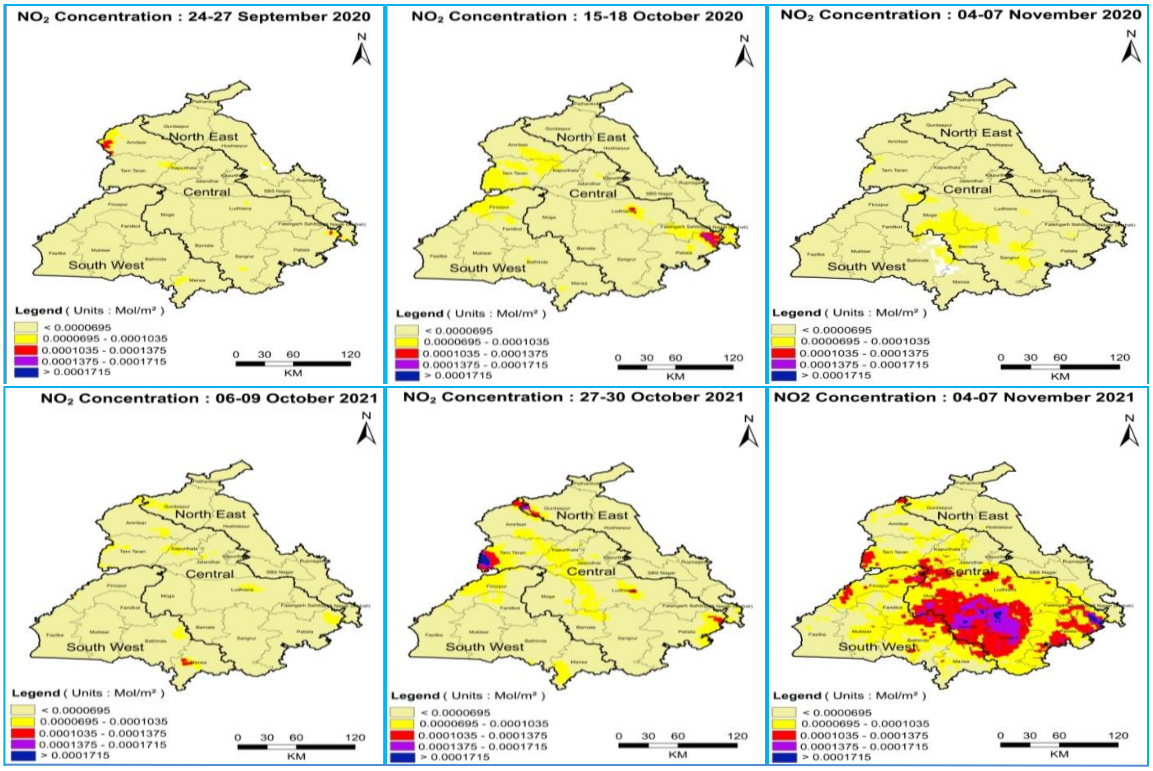


Fig. 6. Spatio-temporal variability in the concentration of NO_2 in Punjab during the rice harvesting period of 2020-21.

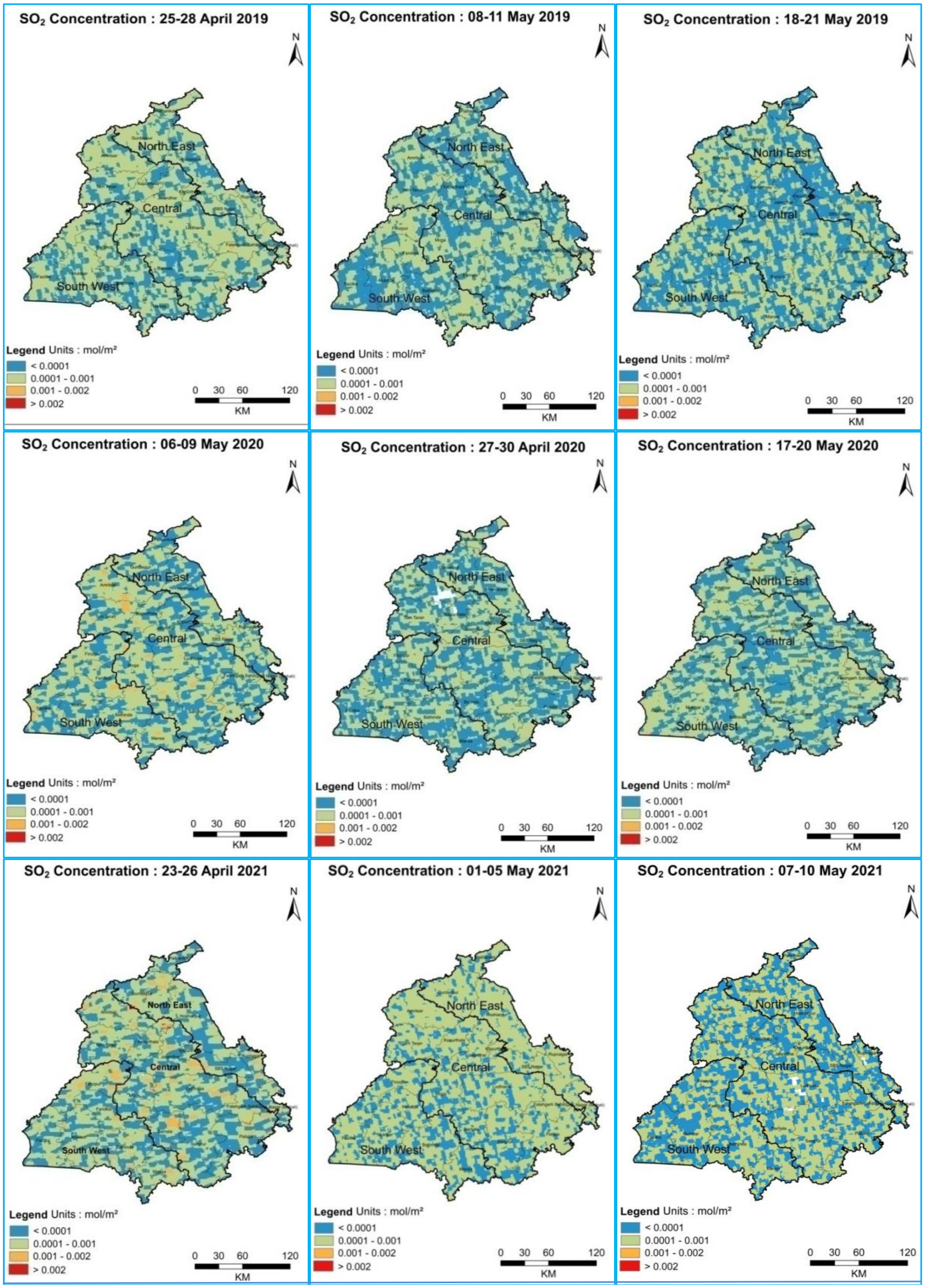
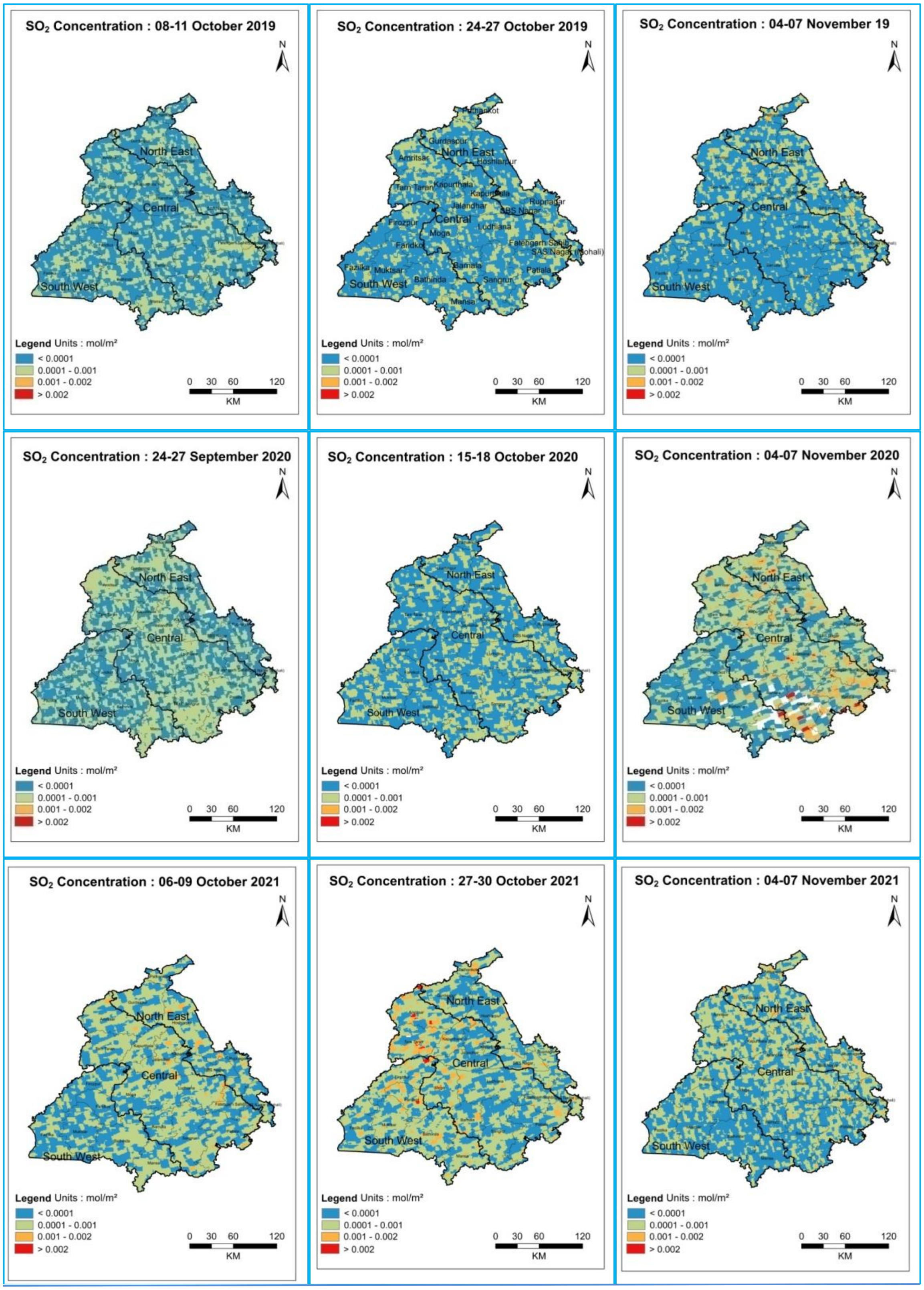


Fig. 7. Spatio-temporal variability in the concentration of SO_2 in Punjab during the wheat harvesting period of 2019, 2020 and 2021.



SO_2 Concentration : 08-11 October 2019

SO_2 Concentration : 24-27 October 2019

SO_2 Concentration : 04-07 November 19

SO_2 Concentration : 24-27 September 2020

SO_2 Concentration : 15-18 October 2020

SO_2 Concentration : 04-07 November 2020

SO_2 Concentration : 06-09 October 2021

SO_2 Concentration : 27-30 October 2021

SO_2 Concentration : 04-07 November 2021

Fig. 8. Spatio-temporal variability in the concentration of SO_2 in Punjab during the rice harvesting period of 2019, 2020 and 2021.

differently in 2021. However, variable trend was observed for NO_2, indicating that other sources of pollution like vehicular and industrial might have influenced these emissions. Similar results were observed by Irfan *et al.*, (2015) as they reported that wheat straw was found to be the major contributor of CO, CO_2, SO_2, NO_x and EC emissions (Fig. 9).

In the central region, $PM_{2.5}$ concentration was found to be the highest in May for all the years under study as this period coincides with the burning of wheat residue after harvesting. Among all the years, $PM_{2.5}$ concentration was observed to be the highest in May 2018 (85.66 µg/m^3), which exceeded both annual and daily recommended standards (Fig. 12) and the lowest was in April-2020 (19.72 µg/m^3) (Fig. 12), which was under the limit, (Fig. 10). A Similar trend was observed for PM_{10} as it was also observed to be highest in May-2018 (160.53 µg/m^3), which has significantly exceeded both annual and daily recommended standards and is really harmful for environment and human health. However its lowest concentration was found in April-2020 (44.63 µg/m^3) (Fig. 12) which is under the ambient concentration. Similar results were found for SO_2. This trend of lowest concentration in the case of particulate matter and SO_2 during April 2020 might be attributed to the lockdown conditions. For NO_2, contrary results were observed among all the years, the maximum concentration was observed in 2021 and it was the highest in March 2021 (52.43 µg/m^3), which has exceeded the annual ambient standards for rural, urban and ecologically sensitive areas (Fig. 12). This might be due to the influence of other sources of emission. For O_3, highest concentration was observed in May 2019 (40.12 µg/m^3), which might be attributed to the highest fire counts in May 2019 (Fig. 10).

Results showed that in general, the highest concentration was found in May (except for 2021, where it was highest in March, however, it was almost similar to May) in the south-west region, which might be due to high burning events in May (Fig. 11). Similar results were observed for PM_{10}. Among all the years, concentration of PM_{10} was found to be minimum for 2020 being 78.47 µg/m^3, 60.62 µg/m^3 and 85.14 µg/m^3 for March, April and May, respectively, which exceeded annual standards but was however lower than daily standards for both industrial, residential, rural and other areas as well as Ecologically sensitive areas. (Fig. 12), which could be due to the effect of lockdown. For SO_2, highest concentration was found in May, which could be because this period coincides with burning activity. For $NO_{2,}$ among all the years the lowest concentration was observed in 2021, which could be due to the lowest fire counts in 2021 for the whole period (March-May) among all the years. The Maximum concentration of NO_2 was found in May 2019 (10.62 µg/m^3), might be due to increased burning during that period. Beig *et al.* (2018) also found similar results.

3.4.2. *Rice harvesting season*

In the north-east region, for the rice harvesting season, analysis showed that, the highest concentration was found in November 2019 (89.71 µg/m^3), which has significantly exceeded both annual and daily recommended standards and the lowest in September 2018 (32.28 µg/m^3) (Fig. 12), which is under ambient standards, in case of $PM_{2.5}$. For $PM_{10,}$ similar trend was observed for all the years (except 2019), which approves of the same reasons as in case of $PM_{2.5.}$ The Highest concentration was found in November 2021 (216.39 µg/m^3), which is almost double of the recommended standards (Fig. 12), which might be attributed to high burning events in November 2021 and the lowest in September 2020 (60.77µg/m^3), which is under recommended daily standard for both industrial, residential, rural and other areas as well as Ecologically sensitive areas (Fig 12). This might be due to low fire events in the period. Vadrevu and Lasko (2018) also reported results on a similar pattern for India as they observed total particulate matter (TPM) emissions in the range of 2.56-63.66 (Gg) per month, with maximum during November. Similar results were observed for SO_2. The concentration was found to be maximum for November 2020 (12.49 µg/m^3), followed by November 2019 (9.98 µg/m^3), and minimum for September 2018 (2.53 µg/m^3). For NO_2, highest concentration was observed in October 2018 (13.39 µg/m^3), which could be due to high fire counts during the period and lowest in September 2021 (4.00 µg/m^3) (Fig. 9) when burning is minimial.

In the central region also, similar analysis was done and in general, particulate matter was found to follow a specific trend, whereas the concentration of gases some variability was observed over the study period. For $PM_{2.5}$, lowest concentration was found in October 2017 (23.46 µg/m^3), which is under recommended standards, but it reached to maximum in the very next month of November-2017 (140.83 µg/m^3), which is 3.5 times the recommended standards for 24 hours for both industrial, residential, rural and other areas as well as Ecologically sensitive areas (Fig. 12). This could be because this period coincides with the residue burning period. Yearly comparison showed an increasing trend in 2019 and 2020 as compared to 2018, which is in accordance with the increase in fire counts from being 27110 in 2018 to 36611 in 2020 (Fig. 2). In 2021, although the concentration of $PM_{2.5}$ comparatively decreased in September, October but it significantly increased during November being 102.75 µg/m^3, which might be attributed to the highest burning events in November. For PM_{10}, similar results

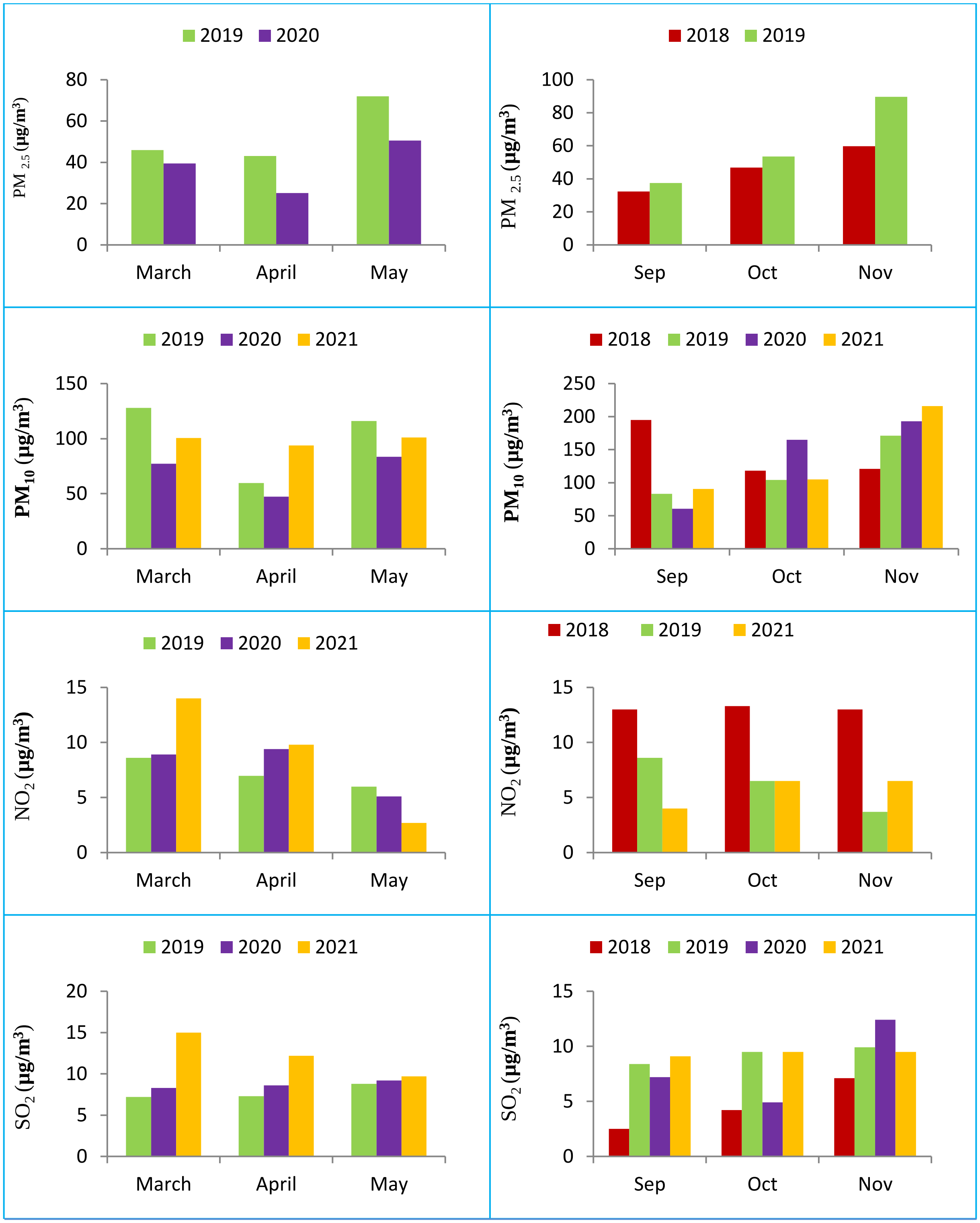


Fig. 9. Temporal variability in the concentration of gases and aerosols (µg/m$^{3)}$ during the wheat and rice harvesting season in the north-east region during 2018-2021.

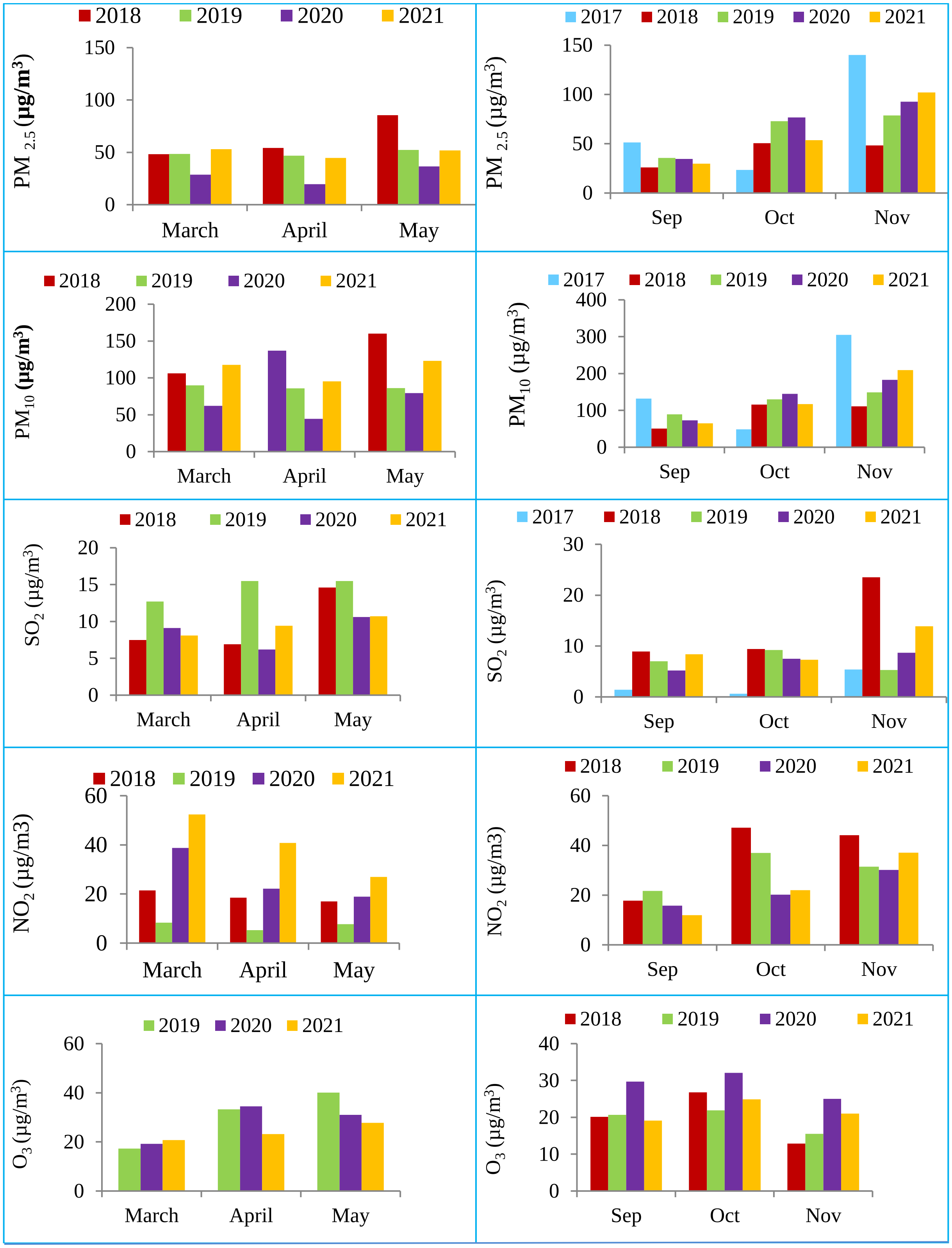


Fig. 10. Temporal variability in the concentration of gases and aerosols (µg/m$^{3)}$ in the central region during the wheat and rice harvesting period during 2017-2021.

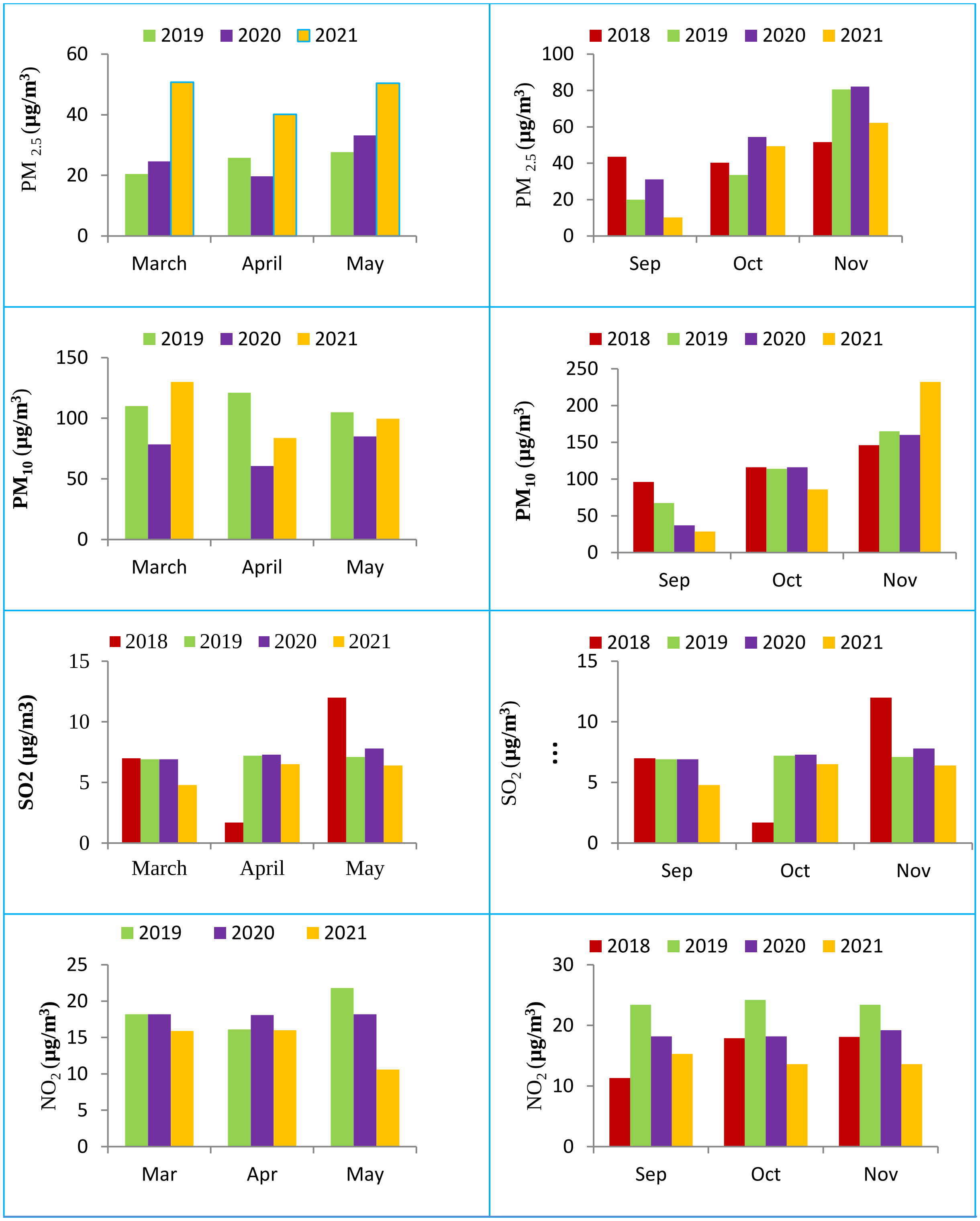
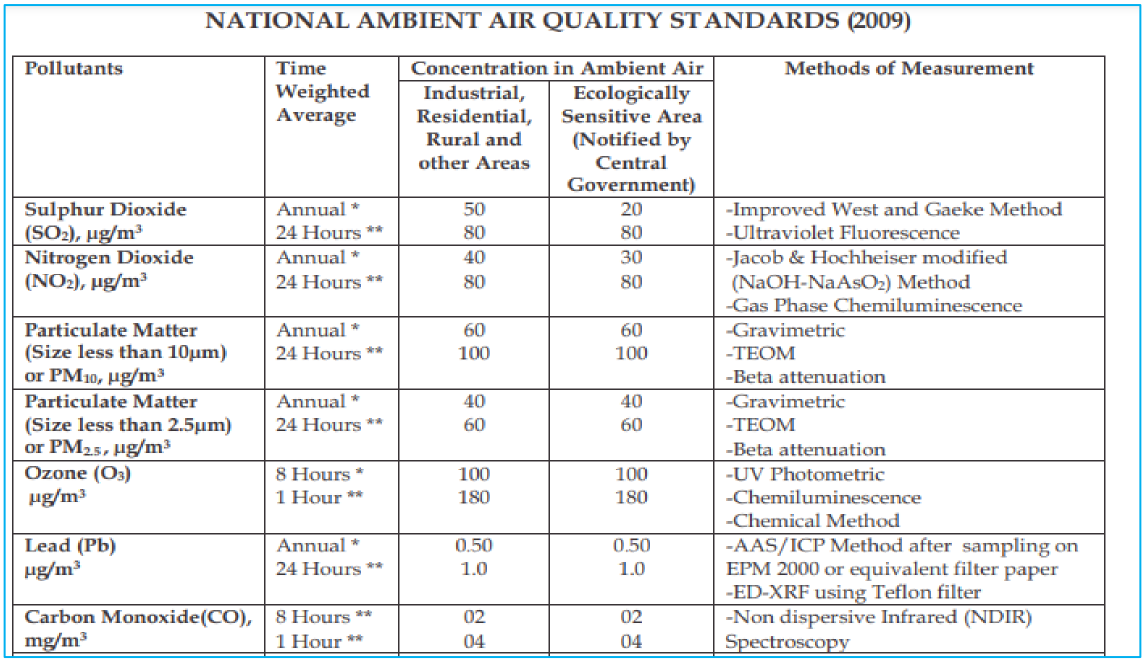


Fig. 11. Temporal variability in the concentration of gases and aerosols (µg/m$^{3)}$ in the south-west region during the wheat and rice harvesting during 2017-2021.



NATIONAL AMBIENT AIR QUALITY STANDARDS (2009)

Pollutants	Time Weighted Average	Concentration in Ambient Air		Methods of Measurement
		Industrial, Residential, Rural and other Areas	Ecologically Sensitive Area (Notified by Central Government)	
Sulphur Dioxide (SO_2), µg/m³	Annual * 24 Hours **	50 80	20 80	-Improved West and Gaeke Method -Ultraviolet Fluorescence
Nitrogen Dioxide (NO_2), µg/m³	Annual * 24 Hours **	40 80	30 80	-Jacob & Hochheiser modified ($NaOH$-$NaAsO_2$) Method -Gas Phase Chemiluminescence
Particulate Matter (Size less than 10µm) or PM_{10}, µg/m³	Annual * 24 Hours **	60 100	60 100	-Gravimetric -TEOM -Beta attenuation
Particulate Matter (Size less than 2.5µm) or $PM_{2.5}$, µg/m³	Annual * 24 Hours **	40 60	40 60	-Gravimetric -TEOM -Beta attenuation
Ozone (O_3) µg/m³	8 Hours * 1 Hour **	100 180	100 180	-UV Photometric -Chemiluminescence -Chemical Method
Lead (Pb) µg/m³	Annual * 24 Hours **	0.50 1.0	0.50 1.0	-AAS/ICP Method after sampling on EPM 2000 or equivalent filter paper -ED-XRF using Teflon filter
Carbon Monoxide(CO), mg/m³	8 Hours ** 1 Hour **	02 04	02 04	-Non dispersive Infrared (NDIR) Spectroscopy

Fig. 12. National Ambient Air Quality Standards (Source: CPCB).

were obtained as concentration was highest in November 2017 (305.88 µg/m^3), which is almost 3 times the recommended standards for 24 hours and minimum in October 2017 (48.64µg/m^3), which is under recommended standards (Fig. 12). Results of $PM_{2.5}$ and PM_{10} in general indicated higher burning during November for all the years. For SO_2, concentration was found to be highest in 2018 among all the years from September to November, despite the low number of fire counts in 2018. This is because SO_2 being a secondary pollutant is influenced by other sources of pollution, like vehicular and industrial emissions also. Similarly, for NO_2, the highest concentration was observed in October 2018 (47.12 µg/m^3) almost at par with November 2018 (44.17 µg/m^3) (Fig 10). The Trend in variation of NO_2 and SO_2 indicated the increase in November could be possibly due to an increase in burning activities during this period. For O_3, the trends vary as this is a secondary pollutant and is affected by other sources also. Saxena *et al.* (2021) studied the effect of $PM_{2.5}$, PM_{10}, NO_2 and SO_2, emitted during crop residue burning, and study revealed that both the rabi and the kharif seasons exhibit a significant increase in pollutant concentrations as they shift from pre-burning to burning. Similar results were observed by Yang *et al.* (2020) by as they inferred from the study that ban on burning proved effective to reduce fire emissions as region-wide $PM_{2.5}$ concentration during the post-harvest season was decreased by 48.1 %.

Similar analysis was done for the south west region for rice harvesting season (March-May) during 2017-2021 (Fig. 11) and similar results were observed to that of the central region, as the highest concentrations were found in November for $PM_{2.5}$, which might be attributed to the highest fire counts in November among all the years. The Lowest concentration of $PM_{2.5}$ was found in September 2021 (10.21 µg/m^3), which is under recommended standards, as the harvesting period had not started yet and the maximum concentration was found in November 2020 (82.16 µg/m^3), which exceeded both annual and daily recommended standards for rural, urban and ecologically sensitive area (Fig. 12). For PM_{10}, similar trend was observed to that of $PM_{2.5}$. Maximum concentration was found in November 2021 (232.62 µg/m^3), which is 2.3 times the recommended standard for 24-hour (Fig. 12). This might be attributed to highest fire counts experienced. For SO_2, the highest concentration was found in November 2018 (12.08 µg/m^3). For NO_2, among all the years the highest concentration was found in the year 2019. The Highest concentration was found in October 2019 (24.26 µg/m^3) followed by November 2019 (23.45 µg/m^3) (Fig. 11). Similar results were reported by Abdurrahman *et al.* (2020) as they observed that burning of residue leads to an increase in the concentration of greenhouse gases in the atmosphere. This variation in NO_2 and SO_2 from aerosols is due to the reason that their emissions are influenced by other sources also. Similar results were observed by Kumari *et al.* (2021) as they reported that the ionic composition of aerosol was also observed to increase to about 84 %, indicating the formation of secondary aerosols during haze.

TABLE 1

Correlation of fire counts with mean temperature relative humidity and sunshine hours during wheat and rice harvesting period in different agro climatic zones of Punjab for 2017-2021. (n=30).

		Mean temperature					Relative humidity					Sunshine hours				
Zones	Months	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
North-East	May	0.43*	-0.38*	-0.05	0.17	0.07	0.43*	-0.04	-0.19	-0.43*	0.02	0.38*	0.19	0.17	0.3	0.28
	October	-0.74*	-0.58*	-0.67*	-0.64*	-0.25	-0.4	0.21	-0.51*	-0.56*	-0.42*	-0.45*	-0.31	0.03	-0.05	0.28
	November	0.55*	0.23	0.55*	0.63*	0.70*	0.17	0.2	-0.47*	-0.62*	-0.23	0.02	0.23	0.49*	0.3	0.05
Central	May	0.12	-0.3	0.06	0.06	-0.10	-0.42*	0.17	-0.03	-0.37*	-0.06	0.17	0.17	0.1	0.38*	0.13
	October	-0.89*	-0.64*	-0.5	-0.88*	-0.43*	0.15	-0.09	-0.33	-0.53*	-0.62*	-0.65*	-0.44*	-0.36*	-0.29	0.18
	November	0.50*	0.31*	0.48*	0.73*	0.66*	0.13	-0.21	-0.40*	-0.64*	-0.36*	-0.34	-0.08	0.19	0.12	-0.45*
South-West	May	0.15	-0.37	0.09	-0.29	0	-0.17	0.41*	-0.14	0.07	-0.40	0.2	-0.13	0.04	-0.03	-0.21
	October	-0.94*	-0.53*	-0.65*	-0.86*	-0.58*	-0.21	-0.05	-0.2	-0.38*	-0.54*	-0.82*	-0.70*	-0.24	-0.78*	-0.01
	November	0.16	0.37*	0.67*	0.78*	0.73*	0.11	-0.14	-0.24	-0.24	-0.34	-0.14	-0.37*	0.01	-0.29	-0.18

3.5. *Correlation of climatic variables, aerosols and gases with fire counts*

3.5.1. *Mean temperature*

In the north-east region, mean temperature was found to be significantly positively correlated in May 2017, whereas in October for all the years except 2021 the correlation was found to be significantly negative. However, in November 2017, 2019, 2020 and 2021, correlation was found to be significantly positive being 0.55, 0.55, 0.63 and 0.70 respectively. In the Central region, correlation was significantly positive in November 2017, 2019, 2020 and 2021, r being 0.50, 0.48, 0.73 and 0.66 respectively (Table 1). Similar results were observed for the South-West region.

So, in general a positive correlation was observed between fire counts and mean temperature in the month of November, which might be attributed to the stable and inversion like conditions as a result of increased accumulation of gases and particulate matter in the air due to crop residue.

3.5.2. *Relative humidity*

In the north-east zone, relative humidity was found to be significantly negatively correlated in May 2020 (r = -0.43). Similarly, for the wheat harvesting season, in November 2019 and 2020 the correlation was found to be significantly negative being -0.47 and -0.62 (Table 1). Similar results were found for the central zone in the months of May (for wheat harvesting season) and November (for rice harvesting season). In the south-west region correlation was found to be significantly negative for May 2021, October 2020 and 2021 being -0.40, -0.38 and -0.54 respectively. Thus, in general, negative correlation was observed between fire counts and relative humidity, which indicated that the increase in fire counts resulted in dryness in the air, which might be attributed to the increase in temperature due to the crop residue burning events (Table 1).

3.5.3. *Sunshine hours*

In the north-east region, the correlation of sunshine with fire counts was found to be significantly negative in October 2017 (-0.45). Similar results were found for the central region as correlation was found to be significantly negative in October 2017, 2018 and 2019 being -0.65, -0.44 and -0.36 respectively. In November 2021 correlation was found to be significantly negative being -0.45. In the south-west region also, correlation was observed to follow the same pattern. Thus, in general, a negative correlation was observed between fire counts and sunshine hours, which might be attributed to the concentration of gases and PM as a result of crop residue burning events (Table 1).

3.6. *Correlation of fire counts with concentration of aerosols and gases during wheat and rice harvesting period*

3.6.1. *PM$_{2.5}$*

Spearman's Correlation Coefficient was studied between PM$_{2.5}$ during the wheat and rice harvesting period of 2017-2021 and fire counts and it was found that in the north-east region, correlation was significantly positive in May 2019, 2020, October 2019, 2020

TABLE 2

Correlation of fire counts with concentration of $PM_{2.5}$ and PM_{10} during wheat and rice harvesting period in different agro climatic zones of Punjab for 2017-2021. (n=30).

Aerosols	$PM_{2.5}$					PM_{10}				
Years	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
North-east										
May	-	0.24	0.44*	0.76*	-	-	-0.17	0.44*	0.38	-0.16
October	-	0.31	0.64*	0.88*	-	-	0.24	0.13	0.90*	0.56*
November	-	0.48*	0.3	0.21	0.15	-	0.24	0.23	0.75*	0.27
Central										
May	0.51*	0.54*	0.62*	0.80*	-0.21	0.31	0.59*	0.84*	0.48*	-0.50
October	0.65*	0.43*	0.80*	0.49*	0.76*	0.52*	0.54*	0.78*	0.37*	0.74*
November	0.11	0.21	0.33	0.22	0.76*	-0.02	0.05	0.34	0.15	0.73*
South-west										
May	-	-	-0.1	0.31	-0.51	-	-	0.25	0.51*	-0.58
October	-	0.87*	0.71*	0.90*	0.70*	-	0.92*	0.82*	0.91*	0.81*
November	-	0.67*	0.24	0.48*	0.3	-	0.32	0.2	0.40*	0.77*

and November 2018, r being 0.44, 0.76, 0.64, 0.88 and 0.48 respectively. Similarly, in the central region, correlation was found to be significantly positive in May for all the years except 2021 and in October for all the years. Similar results were observed for the south-west region as, correlation was found to be positive for all months except for May 2019 and 2021, it was significantly positive in October 2018, 2019, 2020, November 2018 and November 2020, r being 0.87, 0.71, 0.90, 0.67 and 0.48, respectively. The significant correlation of $PM_{2.5}$ revealed the deteriorating effect of crop residue burning on the quality of air, which can lead to severe health implications in the region (Table 2**).**

3.6.2. *PM_{10}*

Similar analysis was done for PM_{10} and it was observed that in the north-east region, correlation was significantly positive in May 2019, October 2020, 2021 and November 2020, the correlation coefficient r being, 0.44, 0.90, 0.56 and 0.75 respectively. In the central region also, correlation was found to be significantly positive in May 2018, 2019, 2020 and in October for all the years. Similar results were observed for the south-west region as the correlation was significantly positive in May 2020, October 2018, 2019, 2020, 2021, November 2020 and 2021 being 0.51, 0.92, 0.82, 0.91, 0.81, 0.40 and 0.77 respectively (Table 2**).**

The significant positive correlation indicated that an increase in the number of fire counts leads to increase in the number of fire events leading to increase in the concentration of PM_{10}, thus, leading to the deterioration of air quality in the region.

3.6.3. *NO_2*

Similar analysis was done for NO2 for the rice and wheat harvesting period of 2017-2021. It was observed that in the north-east region, correlation was significantly positive in October 2020, r being 0.68. In the central region also, correlation was found to be significantly positive in May 2018, 2021 and October 2017, 2018 and November 2021, r being, 0.41, 0.57, 0.74, 0.44 and 0.79 respectively. In the south-west region, the correlation was found to be significantly positive in May 2019, October 2019, 2020 and 2021, November 2020 and 2021 being 0.46, 0.66, 0.64 and 0.39 respectively (Table 3**).**

3.6.4. *SO_2*

Similar analysis was done for SO_2 for rice and wheat harvesting period of 2017-2021. It was observed that in the north-east region, correlation was significantly positive in May 2020, October 2018, 2019, 2021 and November 2019, r being 0.49, 0.62, 0.78, 0.44 and 0.37 respectively. Similar results were observed for the central region as correlation was found to be significantly positive in May 2020, 2021 and October 2017 being 0.40, 0.46 and 0.41 respectively. In the south-west region the correlation was found to be significantly positive in May 2020,

TABLE 3

Correlation of fire counts with concentration of NO_2 and SO_2 during the wheat and rice harvesting period in different agroclimatic zones of Punjab for 2017-2021. (n=30).

Gases	NO_2					SO_2				
Years	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
North-east										
May	-	0.05	0.11	-0.37	-	-	0.1	0.09	0.49*	0.21
October	-	0.02	-0.75*	0.68*	0.12	-	0.62*	0.78*	-	0.44
November	-	-0.15	-0.24	-0.50*	0.27	-	-0.06	0.37	-0.51	0.17
Central										
May	0.24	0.41*	-0.31	-0.09	0.57	-0.64*	-0.01	-0.12	0.40*	0.46*
October	0.74*	0.44*	0.22	-0.07	0.19	0.41*	-0.64*	0.21	-0.14	0.21
November	-0.33	-0.04	-0.44	0.07	0.79*	-0.52	0.35	-0.55*	-0.2	0.13
South-west										
May	-	-	0.46*	0.26	-0.46	-	-	0.11	0.39*	-0.37
October	-	-0.3	0.66*	0.64*	0.39*	-	0.21	-0.05	0.32	0.59*
November	-	0.27	-0.12	-0.72*	0.09	-	0.2	0.38*	-0.25	0.17

October 2021 and November 2018, r being 0.39, 0.59 and 0.38 respectively (Table 3**)**. A critical analysis of the correlation of fire counts with the concentration of pollutants indicated that particulate matter (both $PM_{2.5}$ and PM_{10}) were positively correlated with fire counts in all the regions, whereas in the case of NO_2 and SO_2, variable response has been observed as correlation was not positive in all the regions and months, but during some instances, it was observed to be negative. These results indicated that crop residue burning results in significant addition of particulate matter in the atmosphere (both $PM_{2.5}$ and PM_{10}). But variable response in NO_2 and SO_2 indicate that other sources, such as industrial processes and vehicular pollution *etc*. are also responsible for the emissions into the atmosphere.

4. Conclusions

Continuous near real time monitoring of stubble burning is needed for the mitigation strategies to be implemented effectively. In light of this, monitoring active fire occurrences caused by stubble burning using satellite remote sensing is beneficial. The advantage of remote sensing is that it offers repeating, multi-temporal, multispectral coverage of vast areas at a low cost, which helps with mitigation efforts. The present study on analyzing the spatial-temporal distribution of active fire locations from 2017-2021 for wheat (March-May) and rice harvesting season (September - November) at zone and district level for Punjab Pradesh suggests a latent use of satellite datasets for effective monitoring. The VIIRS at (375 m) sensor was able to detect fire events effectively because of its improved fitness to capture small fires using the I-Band.

A Sudden increase was observed in burning across all the three states during the end week of October and beginning of November. The Central region was found to experience maximum burning, followed by the south-west and north-east respectively. In the wheat harvesting season, maximum burning points in Punjab were observed in the year 2019, being 2535, 11602 and 6212 in north-east, central and south-west regions respectively. whereas for the rice harvesting season, highest fire counts were observed in 2021 in being 40960 and 30351 in the central and south-west regions respectively, while for the north-east region they were highest in 2020, being 2857. Mean temperature was found to be positively correlated while relative humidity was found to be negatively correlated with fire counts for most of the period. Analysis of the concentration of aerosols for the north-east region showed that concentration was found to be highest in November 2021 (216.39 $\mu g/m^3$) which might be attributed to high burning events during that month and lowest in September 2020 (60.77 $\mu g/m^3$) as burning is minimal in September. In addition, this data can be further used to assess global warming potential.

TABLE 4

District and zone wise fire counts for wheat harvesting season from 2017-2021.

Years	2017				2018				2019				2020				2021			
District	March	April	May	Total	March	April	May	Total	March	April	May	Total	March	April	May	Total	March	April	May	Total
Gurdaspur	60	18	1001	1079	76	37	1007	1120	69	28	1126	1223	41	8	1117	1166	38	12	831	881
Pathankot	0	10	181	191	1	12	158	171	4	6	209	219	1	4	160	165	3	17	200	220
Hoshiarpur	60	26	368	454	50	42	390	482	48	24	535	607	60	12	470	542	44	69	410	523
Rupnagar	8	4	87	99	6	5	164	175	9	1	158	168	3	0	73	76	7	10	129	146
SBS Nagar	24	13	197	234	6	8	212	226	23	4	291	318	10	1	192	203	7	6	238	251
Norh-east	152	71	1834	**2057**	139	104	1931	**2174**	153	63	2319	**2535**	115	25	2012	**2152**	99	114	1808	**2021**
Amritsar	16	13	1366	1395	38	11	1418	1467	12	3	1669	1684	3	0	1401	1404	3	10	1053	1066
Tarn taran	2	32	1586	1620	6	3	1198	1207	7	3	1470	1480	4	0	1007	1011	2	3	1096	1101
Kapurthala	26	38	415	479	17	59	535	611	11	20	781	812	11	6	576	593	10	56	651	717
Jalandhar	49	19	483	551	68	33	559	660	40	39	887	966	29	6	705	740	19	38	780	837
Ludhiana	19	22	788	829	11	15	1013	1039	16	8	1767	1791	8	3	1102	1113	19	33	679	731
Moga	0	23	1060	1083	1	20	1062	1083	0	8	1301	1309	0	1	1377	1378	1	68	633	702
Barnala	3	28	406	437	2	27	560	589	0	3	683	686	1	0	554	555	0	80	270	350
Fatehgarh Sahib	6	13	201	220	9	6	170	185	6	2	343	351	3	1	128	132	1	16	168	185
Patiala	13	36	446	495	7	25	750	782	4	26	855	885	2	1	505	508	3	96	418	517
SAS Nagar	2	3	59	64	7	3	62	72	2	5	135	142	1	3	31	35	6	40	39	85
Sangrur	12	119	610	741	14	116	1135	1265	16	7	1473	1496	6	1	801	808	3	258	552	813
Central	148	346	7420	**7914**	180	318	8462	**8960**	114	124	11364	**11602**	68	22	8187	**8277**	67	698	6339	**7104**
Mansa	2	38	412	452	0	21	460	481	0	5	647	652	0	4	453	457	0	97	255	352
Bathinda	0	30	789	819	1	55	947	1003	1	5	1328	1334	0	9	1300	1309	3	113	627	743
Muktsar	0	17	547	564	2	10	736	748	2	0	1200	1202	2	4	1111	1117	2	41	825	868
Faridkot	0	7	347	354	1	7	545	553	1	0	648	649	0	1	631	632	3	46	496	545
Firozpur	1	50	1134	1185	2	57	1083	1142	1	11	1444	1456	1	1	1306	1308	2	121	1126	1249
Fazalika	6	57	314	377	5	78	428	511	8	13	898	919	3	4	677	684	0	94	484	578
South-west	9	199	3543	**3751**	11	228	4199	**4438**	13	34	6165	**6212**	6	23	5478	**5507**	10	512	3813	**4335**

TABLE 5

District and zone wise fire counts for rice harvesting season from 2017-21.

Years	2017				2018				2019				2020				2021			
District	September	October	November	Total	September	October	November	Total	September	October	November	Total	September	October	November	Total	September	October	November	Total
Gurdaspur	2	916	420	1338	0	630	408	1038	7	1060	223	1290	22	1774	222	2018	4	659	762	1425
Pathankot	0	8	6	14	0	8	4	12	0	4	2	6	0	10	5	15	0	4	6	10
Hoshiarpur	11	291	114	416	7	65	117	189	1	228	44	273	14	344	73	431	3	170	214	387
Rupnagar	0	153	102	255	0	27	59	86	0	48	59	107	2	137	73	212	0	71	305	376
SBS Nagar	3	354	238	595	1	60	212	273	3	150	87	240	5	93	83	181	0	63	406	469
NORTH-EAST	16	1722	880	**2618**	8	790	800	**1598**	11	1490	415	**1916**	43	2358	456	**2857**	7	967	1693	**2667**
Amritsar	135	878	254	1267	19	851	409	1279	236	902	325	1463	612	1738	287	2637	158	1024	923	2105
Tarn taran	43	2064	711	2818	0	1638	787	2425	47	2219	539	2805	147	698	698	1543	25	2061	1621	3707
Kapurthala	0	893	426	1319	1	309	370	680	3	848	267	1118	9	1222	345	1576	2	804	931	1737
Jalandhar	2	1083	666	1751	0	403	820	1223	1	707	500	1208	9	868	808	1685	1	601	1967	2569
Ludhiana	3	1618	2272	3893	0	348	2425	2773	4	561	1323	1888	19	1212	2725	3956	8	736	4703	5447
Moga	0	932	2178	3110	0	493	3093	3586	1	438	2001	2440	6	873	4630	5509	0	474	5324	5798
Barnala	0	724	2141	2865	0	322	2705	3027	0	393	2090	2483	2	679	3492	4173	0	454	3617	4071
Fatehgarh Sahib	0	1011	325	1336	3	465	362	830	0	433	254	687	2	834	376	1212	0	319	1275	1594
Patiala	3	2783	1235	4021	6	1842	2034	3882	15	1647	1463	3125	23	2772	2150	4945	11	992	4017	5020
SAS Nagar	7	172	14	193	3	156	12	171	11	127	27	165	8	187	23	218	3	156	110	269
Sangrur	5	2980	4090	7075	0	1548	5686	7234	4	1801	3381	5186	7	2728	6422	9157	3	625	8015	8643
Central	198	15138	14312	**29648**	32	8375	18703	**27110**	322	10076	12170	**22568**	844	13811	21956	**36611**	211	8246	32503	**40960**
Mansa	0	1518	2220	3738	0	1090	2887	3977	2	915	2230	3147	0	1064	3785	4849	0	316	4395	4711
Bathinda	0	2257	2254	4511	0	1382	4542	5924	0	912	3726	4638	0	1502	5708	7210	1	884	6745	7630
Muktsar	0	1954	2334	4288	0	1637	3702	5339	0	828	2268	3096	3	1215	3763	4981	0	741	4868	5609
Faridkot	0	1792	1042	2834	0	792	1993	2785	0	632	1254	1886	1	1210	2216	3427	7	676	2842	3525
Firozpur	3	2307	2375	4685	0	2261	3070	5331	2	1914	2023	3939	6	3441	3013	6460	4	928	4696	5628
Fazalika	0	635	1842	2477	0	501	2228	2729	1	283	1313	1597	3	563	2544	3110	1	343	2904	3248
South-west	3	10463	12067	**22533**	0	7663	18422	**26085**	5	5484	12814	**18303**	13	8995	21029	**30037**	13	3888	26450	**30351**

5. Sources of error in satellite data

5.1. *Data obtained through Sentinel 5p Satellite*

It's important to note that the ground measurements may have been affected by potential errors. Specifically, the placement of a specific station might not accurately reflect the entire pixel area, in addition to the substantial uncertainty associated with the NO_2 equipment. In reality, the suggested different models might be more precise than what the statistics suggest.

5.2. *Data obtained through SUOMI-VIIRS*

Satellites capture momentary snapshots of events on Earth as they orbit above. Each detected hotspot or active fire corresponds to the central point of a pixel marked as containing one or more fires or thermal irregularities, such as volcanoes. For MODIS, these pixels are roughly 1 km in size, while for VIIRS; they are approximately 375 m in size. The "location" provided refers to the center of the pixel and may not necessarily be the precise coordinates of the actual fire. The pixel's actual size varies depending on the satellite's scan and track parameters. In most cases, the fire's actual size is smaller than the pixel itself. We cannot determine the exact location or size of the fire with precision. However, we can confirm that at least one fire is present within the marked pixel. Occasionally, multiple active fires may appear in a line, typically indicating the progression of a fire front (Fig. 13).

There are multiple factors that can explain VIIRS might not have detected a fire:

(i) Timing: The fire could have ignited and extinguished between successive satellite observations, leaving no opportunity for detection.

(*ii*) Environmental Conditions: Fires can be obscured by factors such as cloud cover, thick smoke, or the canopy of trees, making them difficult to detect.

(*iii*) Instrumental Issues: There are instances when the satellite instruments are temporarily inoperable, leading to periods where no observations are made. These occurrences can be explored further in the data outages and known issues sections for VIIRS.

(iv) Fire Size and Temperature: Some fires may be too small or have a relatively low temperature, making them challenging to detect. However, the VIIRS 375 meter active fire product offers improved sensitivity, particularly for fires of smaller size, thanks to its higher spatial resolution. Additionally, it performs better during night time observations.

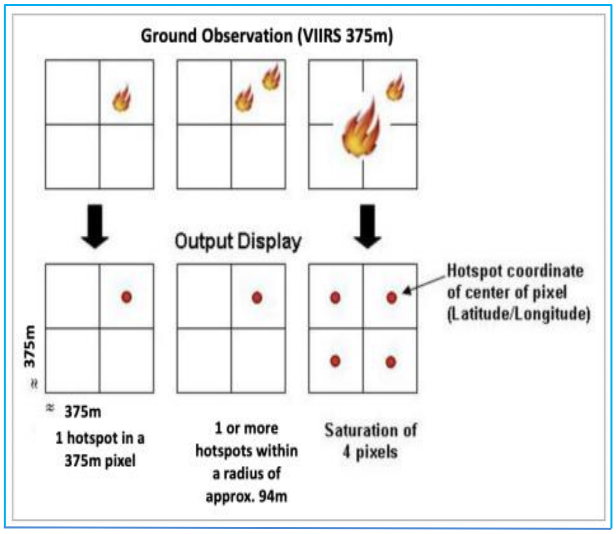


Fig. 13. Reasons behind errors in detection of fire events.

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