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Geospatial Approach for Monitoring of Crop Residue Burning for its Management including Conservation Agriculture

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ABSTRACT

Paddy residue burning after harvest is a common practice followed by farmers in the north western India to clear the land for succeeding wheat crop sowing on time. But it emits particulate matter and greenhouse gases leading to atmospheric pollution in the region. The state governments are implementing schemes for promotion of in-situ management of paddy residue as well as adoption of conservation agricultural practices in sowing of wheat. In order to target schemes for management of paddy residue including adoption of conservation agriculture, it is imperative to have near real-time information on the extent of paddy residue burning along with its current and historical spatio-temporal pattern and the emission of pollutants. This paper covers the use of remote sensing technologies in the whole gamut of spatio-temporal monitoring of crop residue burning and pollution estimation. The work carried out by the CREAMS (Consortium for Research on Agroecosystem Monitoring and Modeling from Space) laboratory of ICAR-IARI (http://creams.iari.res.in) has been taken as an example in the paper to elucidate the methodology and results for the states of Punjab, Haryana and Uttar Pradesh. The residue burning monitoring is an integral part of any strategy to estimate the quantum of problem and to target areas for the promotion of conservation agriculture practices to be undertaken by different agencies.

Key words: Remote sensing, biomass, crop area, pollution, fire event, rice-wheat

Issue of Crop Residue Burning in India

Indian agriculture produces approximately 682 million tons (Mt) of crop residues annually (Jain *et al.*, 2018) from major eleven crops throughout the year. The residues are used for animal feed, soil mulch and manure, thatching for rural houses and fuel for domestic and industrial use and thus, are of tremendous value to farmers. However, a large portion of the residues, about 178 Mt annually is surplus (Jain *et al.*, 2018). It is estimated that about 140 Mt annually, is burned on-farm primarily to clear the field from straw and stubble of the preceding crop for sowing of the succeeding crop.

The residues of rice, wheat, cotton, maize, millet, sugarcane, jute, and rapeseed-mustard are typically burned on-farm in various states of the country. The problem is severe in irrigated agriculture, particularly in the mechanized rice-wheat system of the North-West India. Burning of crop residues leads to 1) release of soot particles and smoke causing human health problems; 2) emission of greenhouse gases (GHGs) particularly carbon dioxide causing global warming; 3) loss of plant nutrients such as N, P, K and S; 4) adverse impacts on soil

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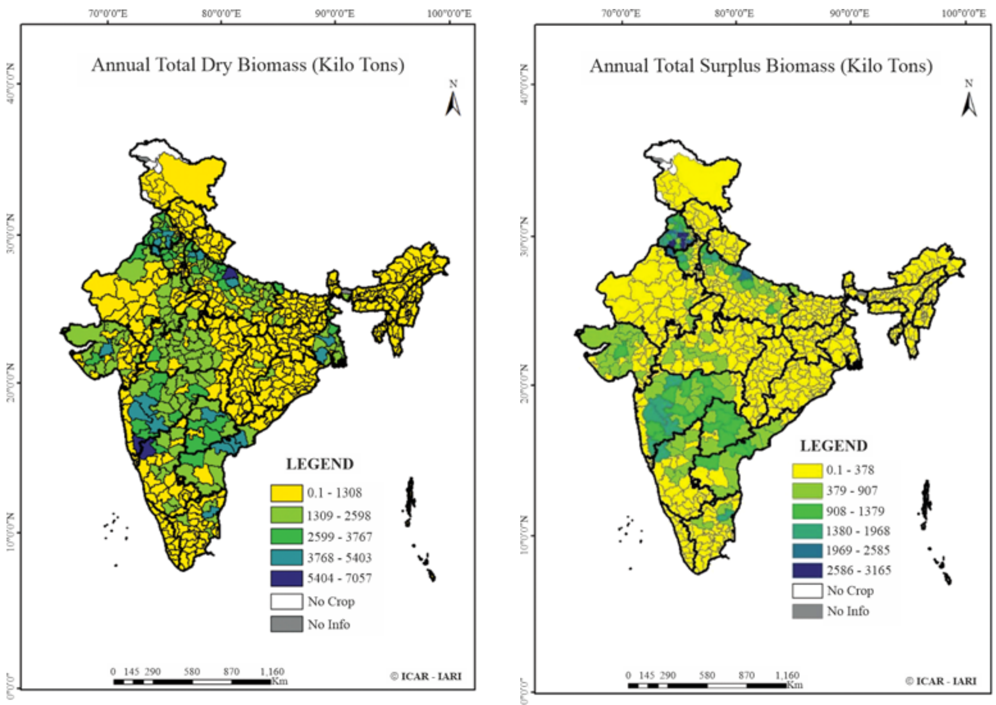


Fig. 1. District-wise total and surplus crop residue produced in India (Jain *et al.*, 2018)

properties and 5) wastage of valuable C and energy-rich residues. In addition to loss of entire amount of C, 80% of N, 25% of P, 50% of S and 20% of K present in straw are lost due to burning. If the crop residues are incorporated or retained, the soil will be enriched, particularly with organic carbon and N. Heat from burning residues elevates soil temperature resulting in elimination of bacterial and fungal populations, which may regenerate after few days. However, repeated burning in the field may permanently diminish the microbial population. It is reported that long-term burning reduces total N, potentially mineralizable N and C in the 0-15 cm soil layer.

Linkage with Conservation Agriculture

The problem of on-farm burning of residues is intensifying in recent years due to unavailability of labor, high cost in removing the residues by conventional methods and use of combine harvester without straw spreading mechanism. Thus, on-site crop residue management strategies could be a sustainable solution for the problem of crop residue burning. Conservation agriculture (CA) offers a sustainable option of *in-situ* crop residue management. The CA has proven to be resource and energy-efficient agricultural crop production (Jat *et al.*, 2020). In the rice-wheat cropping system of North-West India, conservation agricultural practices include zero-till wheat sowing, sowing of wheat with happy seeder and residue incorporation with rotavator and super seeder (Shyamsundar *et al.*, 2019). The benefits of conservation agriculture on improvement of soil physical properties, recycling of soil nutrients, enrichment of soil biota and on crop yields in different cropping-rotations are well documented (Gupta *et al.*, 2007; Lohan *et al.*, 2018).

It is reported that the adoption of CA practices in South Asia has reached only over 3.0 million ha (Mishra *et al.*, 2020) and about 1.5 million ha area is in India (Jat *et al.*, 2021). It shows that there is slower rate of adoption of CA practices in India, in spite of numerous and multi-dimensional benefits of CA over conventional system. Therefore, there is a need to identify the hot-spot areas of crop residue burning where conservation agricultural practices can be promoted. This would be a win-win situation which will not only increase the rate of adoption of CA but also decrease the problem of crop residue and associated problems. In Indian context under rice-wheat system in north-west India, the scope of prioritizing areas for adoption of conservation agricultural practices in wheat, it is imperative to map hot-spots and spatio-temporal patterns in burning of rice residue.

Need and Role of Remote Sensing

It is said about any phenomena that if you can measure it, you can manage it. It is true in the case of crop residue burning. The State and Central Governments are implementing different schemes to prevent on-farm burning of crop residues by the farmers. They need very objective and near real-time information on the extent of burning, its spatio-temporal pattern and emission of pollutants from the residue burning. Besides, they need to have an estimate of the crop residue burning activities, in current year and its comparison with previous years at different administrative units. Traditionally, the estimation of crop residue burning activities was relied upon by indirect methods, such as, collecting limiting ground reports, using a fraction of crop production being burnt where fraction value was based on expert judgment, using coefficients based on IPCC methodologies, etc. (Andrae *et al.*, 1991). These methods suffer from many deficiencies, namely, their limited spatio-temporal coverage of the burning events; subjectivity of enumerators; and thumb-rule based generic coefficients.

With the advancement in space-based imaging technologies, computational power, data analytics techniques, increasingly satellite remote sensing is being employed world over for monitoring of forest fires, residue burning events, mapping the area burned and quantifying the residue burnt (Korontzi *et al.*, 2006). The satellites can be used for near-real time monitoring of burning events using thermal remote sensing sensors, while multispectral satellite sensors are used for mapping the area burnt. Many international satellite constellations are generating experimental global "active fire products" and "burned area products" ranging in spatial resolution from 250m to 1 km (Simon *et al.*, 2004; Tansey *et al.*, 2008; Roy *et al.*, 2005; Giglio *et al.*, 2018; Chuvieco *et al.*, 2018). However, these coarse resolution products underestimate the burned area especially in croplands owing to their low detection capability of small burn patches, inadequate temporal sampling, cloud cover, variability in fuel conditions, differences in fire behavior, and issues related to spatial resolution (Scholes *et al.*, 1996; Eva and Lambin 1998; Kasischke *et al.*, 2003). Active-fire underestimation errors can occur because some fires may be too small to detect, or obscured by clouds, or were not actively burning at the time of satellite overpass. So, high spatial resolution multispectral images of pre and post burning periods are used for mapping and estimating burnt area reliably.

To avoid the crop residue burning, conservation agriculture is an important conservation measure. Conservation agriculture includes conservation tillage along with crop rotation. Intensity of soil tillage is often characterized in terms of amount of surface crop residue cover (CRC). Different sources have defined soil tillage intensity in different manner (Table 1). From the definitions, the conservation tillage system implies 30% or more residue cover. Remote sensing methods have been applied to identify conservation tillage practices with varying degree of success.

This paper provides the summary of studies carried by the CREAM laboratory of ICAR-Indian Agricultural Research Institute (http://creams.iari.res.in) for monitoring of rice residue burning, estimating the area burnt and amount of pollutants emitted for the three states of Punjab, Haryana and Uttar Pradesh using satellite remote sensing (Chhabra *et al.*, 2019). Besides, it reviews the linkages between the rice residue burning and targeting of conservation tillage in wheat using remote sensing technologies.

Monitoring of Burning Events

One of the commonly used applications of satellite remote sensing is to monitor in real-time the residue burning events or active fire events. The real-time detection of the active fire events

Table 1. Soil tillage intensity as a fraction of crop residue cover retained on surface

S. No.	Intensity class	References
1	Intensive tillage: <15% CRC Reduced tillage: 15%–30% CRC Conservation tillage: >30% CRC	CTIC, 2015
2	Conventional or low-residue tillage: 0–30% CRC Conservation tillage: 30–60% CRC High-residue, minimum soil disturbance tillage management: 60–100% CRC	Daughtry *et al.*, 2006
3	Conventional tillage :<15% CRC Low residue tillage: 15–30% CRC Conservation tillage: 30–60% CRC High residue tillage: >60% CRC	Chesapeake Bay Program, 2016

CRC: crop residue cover

for both, day and night, can be accomplished by acquiring the daily thermal datasets from the seven different polar-orbiting satellites during the monitoring period. Table 2 summarizes the details of satellite with their respective sensors, resolution etc. which are used for detecting active fire events. The active fire detection algorithm (Fig. 2) is allocated into two modules; day-time and night-time. Both the modules are driven by fire sensitive Short-Infrared (SWIR), Middle-Infrared (MWIR) and Long-Infrared (LWIR) spectral channels, exploiting the emissivity component of the fires. Fire detection for both day and night is successful for MODIS and VIIRS sensors as they employ a highly sensitive 3.9 µm channel that has a strong thermal response to even a smaller portion of fire in a pixel. The AVHRR on-board NOAA and METOP satellites are used only for detecting night-time fires as they lack the 3.9 µm channel. Using the threshold values for both day and night, the anomalous temperatures are detected with background characterization and thus the pixel is tagged as fire pixel and the intensity of fire is quantified in watt per sq. meter (W/m^2). To identify crop specific fire events, the crop mask or agricultural mask of the study area is to be used. Presence of clouds is a serious drawback of this method as satellites cannot detect the temperature of ground events under such condition.

The thermal data was used by CREAM lab to monitor in real-time the active fire events for rice and wheat in Punjab, Haryana and UP states of north India. Figure 2 shows as an example of active fire events detected on a day in North-west India during October 2018 corresponding to rice

Table 2. List of satellites and sensors used for monitoring active fire events

Space Agency	Satellite	Sensor	Wavelength (µm) for fire event	Spatial Resol. (m)	Passes (Day/Night)
NASA (USA)	S-NPP	VIIRS	3.660 – 3.840 10.263 – 11.263	375	Both
NASA (USA)	AQUA	MODIS	Channel 21 (3.929 – 3.989)	1000	Both
NASA (USA)	TERRA	MODIS	Channel 22 (3.929- 3.989) Channel 31 (10.780 – 1.280)	1000	Both
NOAA (USA)	NOAA-18	AVHRR/3	Channel 3B (3.55 – 3.93)	1100	Night
NOAA (USA)	NOAA-19	AVHRR/3	Channel 4 (10.30 – 11.30)	1100	Night
EUMETSAT (EU)	METOP-1	AVHRR/3	Channel 3B (3.55 – 3.93) Channel 4 (10.30 – 11.30)	1100	Night
EUMETSAT (EU)	METOP-2	AVHRR/3		1100	Night

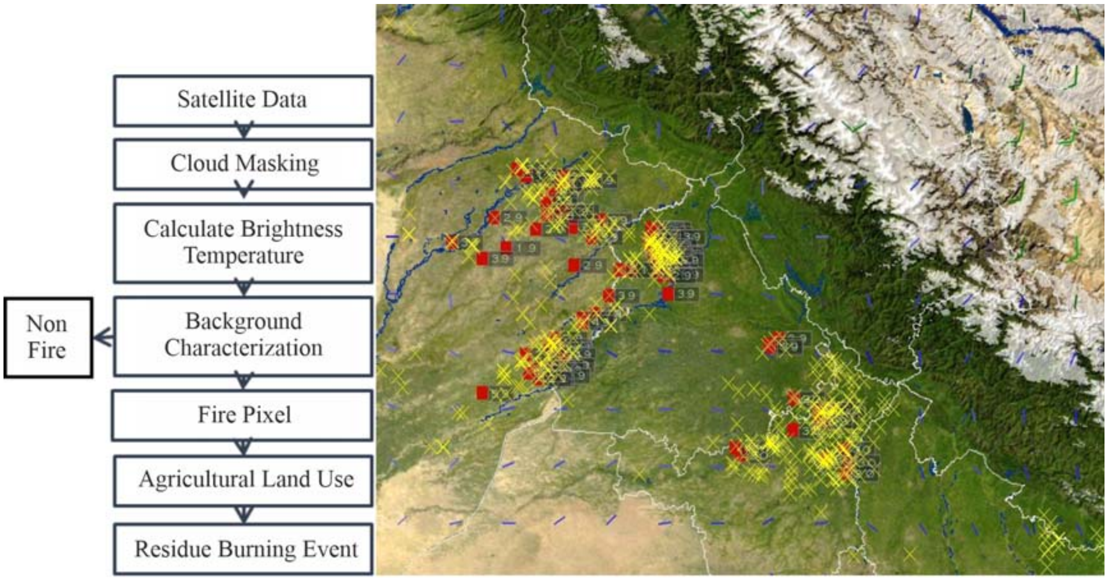


Fig. 2. Left panel shows a flow chart of fire detection algorithm. Right panel shows active fire events detected by satellites S-NPP VIIRS (Yellow) and MODIS (Red) over North-west India on a day in October 2018

harvesting season. The daily monitoring was carried out during 1-Oct to 30-Nov 2018 for rice and 15-Apr to 31-May 2019 for wheat residue burning. The current season events were compared with events happened in previous years to evaluate the increasing or decreasing trends in residue burning practice and identify the hot-spots which should be addressed on priority by stakeholders.

The figure 3 shows comparison of number of rice burning events detected in 2018 with that in 2016 and 2017 in three states. Overall, for the three states, burning events detected were 127774, 88948, and 75563 in the years 2016, 2017 and 2018, respectively. About 15% and 41% reduction in number of burning events were observed in 2018 as compared to that in 2017 and 2016, respectively. Of the 75563 burning events detected in the three States, these were distributed as 59695 (79%), 9232 (12%) and 6636 (9%) in Punjab, Haryana and UP, respectively. The majority of burning happened between 27-Oct and 09-Nov in the three states. The critical

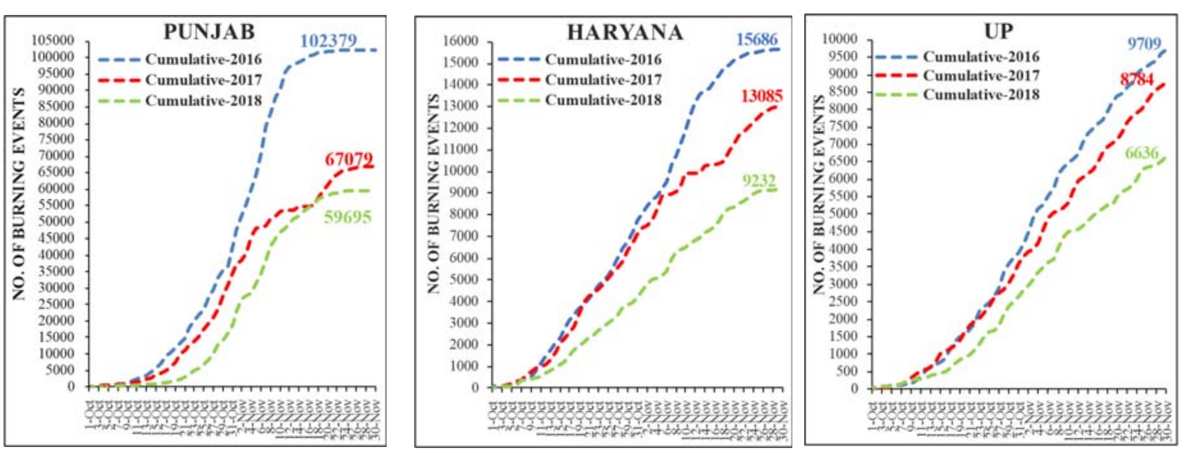


Fig. 3. Comparison of rice residue burning events of 2018 with 2017 and 2016 in the three states of Punjab, Haryana and UP over 1-Oct to 30-Nov 2018 period

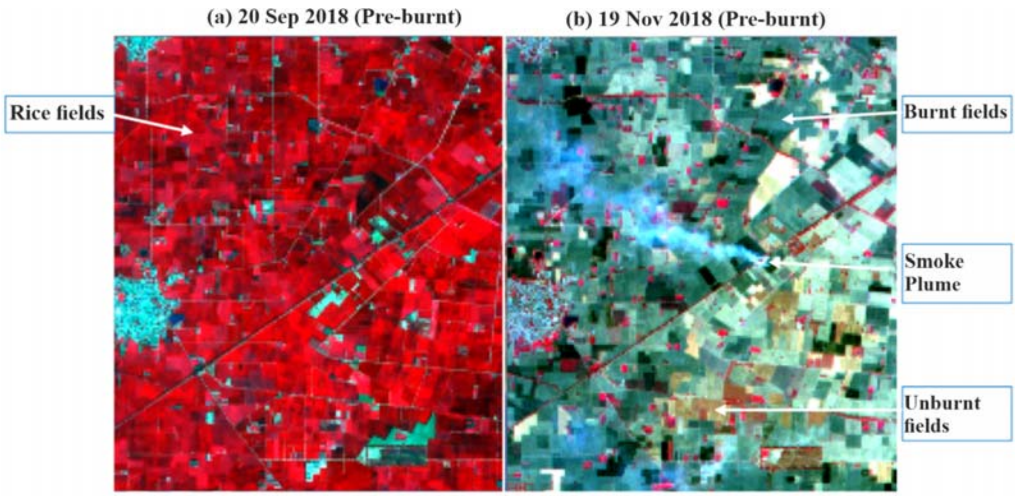


Fig. 4. High-resolution satellite images of pre- and post-burning period used for mapping crop burnt area

information on acquisition date/day of fire, location of the fire (latitude/longitude), confidence of the detected fire, and fire intensity quantified in watt per sq. meter (W/m^2) in the form of daily bulletins was conveyed to each of three State Department of Agriculture (SDAs) for taking suitable action.

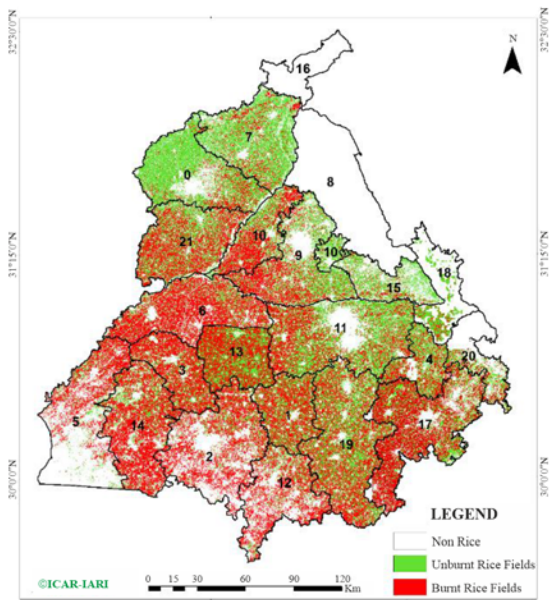
Mapping the Burnt Crop Area

One of the important information sought by managers is the statistics on crop area burnt, their detailed maps aggregated to an administrative boundary. For mapping crop area burnt, multispectral high resolution satellite images can be employed, like, Sentinel-2 MSI with a spatial resolution of 20m (Fig. 4). To estimate and map the burnt areas, Normalized Burn Ratio (NBR) Index (Lutes *et al.*, 2006) is used that combines near-infrared and shortwave-infrared spectral channels. This index is quite helpful in mapping burnt areas as the reflectivity of burnt areas is higher in short wave channels and lower in near infrared channels. Further, to map the severity of the burnt areas, change in NBR can be estimated by subtracting NBR of post-event from NBR of pre-event. A higher value of dNBR indicates higher burn severity and a negative burnt severity indicates post-fire growth. To accurately estimate the burnt and unburnt pixel, a threshold-based approach combining dNBR and NDVI of post event can be also used. A rice mask is then applied and maps indicating burnt and non-burnt areas are generated. The sub-district and district-wise total rice burnt area statistics can be generated. Further, the estimate of burnt area can be used to estimate the amount of straw/residue burnt. Amount of residue burned in the field can be taken as the amount of straw produced in rice area burnt estimated from remote sensing. The amount of straw produced can be estimated empirically by multiplying the crop yield figure with ratio of straw to grain yield and factor for moisture content.

The figure 5 shows map of rice burnt and district-wise statistics of rice area, area burnt and straw burnt. For the 22 paddy growing districts of Punjab, remote sensing estimated 3.07Mha area planted, out of which 1.51 Mha area was burnt in 2018 *i.e.*, about 49% of the paddy planted area reported burning. Remote sensing estimated 26.2 Mt of paddy straw produced on dry weight basis in these 22 districts, out of which 11.8 Mt was burnt in 2018 *i.e.*, 45% of paddy straw was burnt. Further, 2004 villages out of total 12627 rice growing villages were identified from these maps in which no burning occurred.

Estimating Pollutant Emission

Burning of crop residue emit pollutants which degrade the air quality and have serious implications for the health of humans and animals



District	Paddy area by RS ('000 ha)	Paddy Area Burnt by RS ('000 ha)	Percent Burnt Area by RS (%)	Straw production on dry wt basis ('000 tons)	Straw Burned on dry wt basis ('000 tons)	Straw Burned (%)
AMRITSAR	186.76	33.72	18.06	1228.99	199.30	16.22
BARNALA	118.42	66.99	56.58	1125.88	572.04	50.81
BATHINDA	154.91	121.18	78.22	1449.35	1018.08	70.24
FARIDKOT	116.25	84.42	72.63	976.27	636.75	65.22
FATEHGARH SAHIB	81.88	36.18	44.19	795.92	315.84	39.68
FAZILKA	103.96	78.56	75.57	755.85	512.93	67.86
FIROZPUR	189.11	147.48	77.99	1651.04	1156.23	70.03
GURDASPUR	181.17	35.90	19.81	1190.18	211.77	17.79
HOSHIARPUR	74.0		6.37	592.37	33.90	5.72
JALANDHAR	166.27	75.73	45.55	1411.07	577.16	40.90
KAPURTHALA	118.02	62.09	52.61	997.06	471.05	47.24
LUDHIANA	255.71	101.52	39.70	2541.12	905.94	35.65
MANSA	111.40	84.49	75.85	986.67	672.05	68.11
MOGA	152.01	82.35	54.17	1438.34	699.73	48.65
MUKTSAR	186.58	142.17	76.19	1556.01	1064.67	68.42
NAWASHAHR	65.76	12.22	18.59	588.19	98.17	16.69
PATHANKOT			1.02	158.93	1.45	0.91
PATIALA	231.49	92.67	40.03	2026.47	728.50	35.95
RUPNAGAR	34.56		17.92	322.85	51.94	16.09
SANGRUR	290.37	143.14	49.30	2921.20	1293.15	44.27
SAS NAGAR	32.56		6.54	242.80	14.27	5.88
TARN TARAN	187.58	100.38	53.51	1278.05	614.15	48.05
TOTAL	**3066.77**	**1514.51**	**49.39**	**26234.61**	**11849.07**	**45.16**

Fig. 5. Rice burnt area and district-wise statistics generated for Punjab in 2018 using high resolution Sentinel-2 MSI images

in the affected region (Vadrevu *et al.*, 2014; Jain *et al.*, 2014). Satellites not only detect the burning incidents but they can also measure the intensity of fire, in terms of, radiative power of fire event from the literature (Boschetti *et al.*, 2009). It was found that fire radiative power (FRP) and fire radiative energy (FRE) of burnt residue is directly related to amount of gaseous species emitted from that burnt straw. In the study example for rice residue burning in three northern states in 2018, the different species of environmental pollutants viz., methane, nitrous oxide, CO_2, CO, PM2.5 and PM10 emitted into atmosphere were estimated using fire radiative power of residue burning events as measured by satellites. Figure 6 shows the maps of Tehsil-wise CO_2 and Particulate Matter (PM2.5) emission by rice residue burning in Punjab as estimated by satellites.

Hot-spot Areas of Paddy Residue Burning and Potential Areas for CA Practices Intervention

The map of paddy burnt area generated from Sentinel-2 satellite images and district-wise statistics of active fire events for the year 2020 (Fig. 7) shows that Sangrur, Bhatinda and Firozpur are the hot-spot districts in Punjab, where maximum crop residue burning took place in the year 2020. Therefore, these are the areas in Punjab where CA interventions should be initiated on priority basis. Similarly, in Haryana, districts of Fatehabad, Kaithal and Karnal are the hot-spot areas of paddy residue burning. Such information becomes handy for the policy makers to target schemes of providing equipment for conservation tillage and undertaking awareness and capacity building activities of farmers in adoption/use of such equipment.

Spectral Indices for Conservations Tillage

Traditional measurement of residue cover in crop fields includes roadside surveys, photographic methods and line-point transects (Morrison *et al.*, 1993). Conventional methods for crop residue cover estimation are tedious, time consuming and subject to operator bias. Numerous remote sensing-based techniques were developed for estimation of crop residue cover. However, formulation of spectral indices for assessing crop residue cover is difficult because soils and crop residues lack unique spectral signatures in the 400–1100 nm region (Aase and Tanaka 1991; Daughtry *et al.*, 2005). Crop residues have unique spectral absorption features

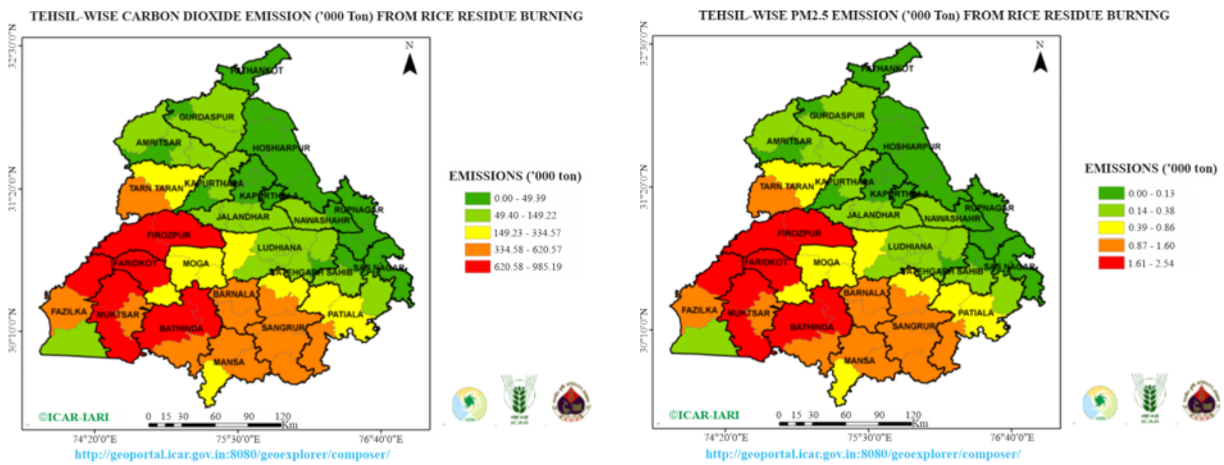


Fig. 6. Maps of CO_2 and particulate matter emitted by rice residue burning for Punjab in 2018

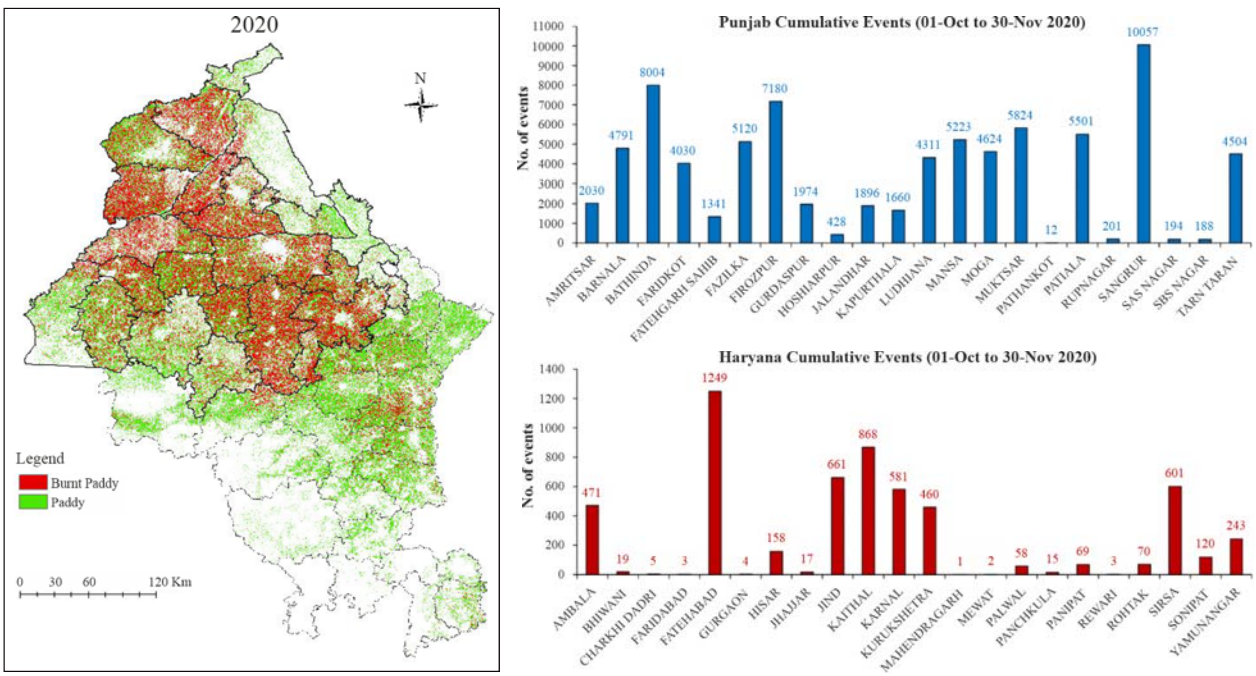


Fig. 7. Map of rice burnt area and district wise statistics of active fire events in Punjab and Haryana in the year 2020

that allow them to be discriminated from soils and vegetation based on their reflectance spectra in SWIR region. They are largely composed of cellulose and lignin, which exhibit absorption features near 2100 nm and 2300 nm. Additionally, crop residues tend to have a general decrease in spectral reflectance from 1600 nm to 2300 nm, in contrast to soils for which spectral reflectance remains relatively constant from 1600 to 2300 nm.

Various remote sensing methods such as linear spectral unmixing, spectral index and triangle space have been developed. Among the spectral indices, Normalized Difference Tillage Index (NDTI) (Van Deventer *et al.*, 1997), dead fuel index (DFI) (Cao *et al.*, 2010), normalized difference senescent vegetation index (NDSVI) (Qi *et al.*, 2002), the normalized difference index (NDI, NDI5, and NDI7) (Mcnairn and Protz, 1993), the short-wave near-infrared normalized difference residue index (SRNDI) (Jin *et al*., 2015), the cellulose absorption index (CAI) (Daughtry *et al*., 1996), the shortwave infrared normalized difference residue index (SINDRI) (Serbin *et al*., 2009), and lignin cellulose absorption index (Daughtry *et al*., 2005) have been used for assessing and mapping conservation tillage practices.

Summary

Globally, satellite images are increasingly being employed to monitor active fire events and related applications for providing observations to better manage the crop residue. Government of India is also making use of this technology in India to not only monitor specific region during particular time of the year for crop residue burning but also using it for pan-India monitoring. Development of techniques for use of this technology to discriminate conservation tillage fields is work-in progress as some spectral indices using SWIR band have shown promise. This technology is objective and has been found to be fairly useful by different stakeholders, including by the line department officials in the States. Though reliable, this technology has certain drawbacks also. Active-fire underestimation errors can occur because some fires may be too small to detect, or are obscured by clouds, or were not actively burning at the time of the satellite overpass. Also, it is difficult to relate them to actual area burned due to inadequate temporal sampling, variability in fuel (residue) conditions and cloud cover, differences in fire behavior, and issues related to spatial resolution. Some of these drawbacks may be addressed in near future as more and more satellites are being launched with channels sensitive to fire events and with improved spatial and spectral resolutions, together with improvement in image analytics and data mining methods. The research efforts towards developing a system is in progress using remote sensing where a combination of mapping rice area not burnt followed by conservation tillage in subsequent wheat crop in north west India will be able to provide reliable area estimates and its dynamics over years.

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