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MODIS-Derived Fire Characteristics and Greenhouse Gas Emissions from Cropland Residue Burning in Central India

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Abstract: Cropland residue burning is one of the major causes of the emission of greenhouse gases and pollutants into the atmosphere, and is a major global environmental problem. This study analyzes the spatiotemporal changes in greenhouse gas emissions from cropland residue burning in Chhattisgarh, India. The Moderate Resolution Imaging Spectroradiometer (MODIS) active fire data was analyzed over a 21-year (2001–2021) period, and associated greenhouse gas emissions were estimated. A total of 64,370 fire points were recorded for all land cover types. The number of cropland fires increased from 49 to 1368 between 2001 and 2021, with a burning peak observed between December and March. Fires in cropland areas contributed to 32.4% (19,878) of the total fire counts in the last 21 years. The total estimated emissions of greenhouse gases between 2001 and 2021 ranged from 421.5 to 37,233 Gg, with an annual rate of emission of 8972 Gg from wheat residue burning, and from 435.45 to 64,108.1 Gg, with an annual emission of 15,448.16 Gg from rice residue burning. The Chhattisgarh plain region was the cropland fire hotspot of the state. The present study indicates increased cropland residue-burning activity in Chhattisgarh. Therefore, there is an immediate need to develop sustainable alternative methods for agricultural residue management and eco-friendly methods for the disposal of crop residues.

Keywords: cropland residue burning; GHGs; MODIS active fire; GIS; Chhattisgarh

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1. Introduction

Global climate change, caused predominantly by the emission of greenhouse gases (GHGs), is a major concern in the world. Some GHG emissions occur naturally, while others are anthropogenic. Overall levels of greenhouse gases have increased drastically in recent times [1–3]. The burning of crop residue has been recognized as a major source of greenhouse gases and other pollutants in the atmosphere, causing adverse environmental and human health effects [4,5]. Globally, most farmers use fire as a tool for the removal of crop residue from the agricultural field for the preparation of the next round of crops [6,7]. Although some amount of crop residue burning may be useful for the management of agricultural fields, including reducing the risks of crop diseases, controlling weeds, and improving soil fertilization [8], it negatively affects the regional and global air quality and climate [9–11]. Crop residue burning is one of the largest types of biomass burning in the globe, accounting for 10% of the total global annual fire incidences [8,12].

India is an agricultural country with the highest net shown area in the world, and approximately 58% of the population derive their livelihoods from farming activities. Its major production is rice–wheat crops. The agricultural system produces large amounts of crop residue every year, in the form of cereal straws, woody stalks, and other crop wastes [13,14]. Out of these crop residues, some amounts are generally used as animal fodder, residential cooking, and in local industries as fuel [15], but a huge amount of residue is not properly utilized, and is left in the agricultural fields. The crop residues in agricultural fields have become a significant challenge. It requires money and time to remove residues through labor, so farmers burn residues in the same agricultural field, thus saving time and money [16–18]. Such crop residue burning has been noticed in the last two or three decades [19,20]. In India, a total of 347 Mt of crop residue was generated in the year 2000, of which rice and wheat residue accounted for about 90% [21], and this number increased to 585 Mt in 2018 [1], which indicates a seriously alarming situation. Crop residue burning has been a common practice in Indo-Gangetic plains, especially in Panjab and Haryana, in recent decades. In the states of Haryana, Punjab, and Himachal Pradesh, 80% of the produced rice straw was burned in situ, while only 15% and 50% of the rice straw was burned in Uttar Pradesh and Karnataka, respectively [13]. The crop residue burning in Central India has significantly increased during the last fifteen years due to the use of combined harvesters [13,22]. Crop residue burning has also become widespread in Chhattisgarh in the last few years.

The Remote Sensing (RS) and Geographic Information Systems (GIS) techniques played an important role in understanding and estimating cropland fire areas, detecting active fire and its behavior, and mapping burned areas [23–25]. Satellite-based remote sensing data provide opportunities to monitor cropland residue burning in a large area [26], and this method has been used for more than two decades for the mapping and monitoring of global forest and cropland fires [27–30]. In many parts of the world, the monitoring and mapping of global forest fires have been reported [29–32], but reports on cropland fires in the scientific literature are limited, especially in Central India [8]. In this study, we quantified spatiotemporal patterns with monthly and seasonal patterns of cropland residue burning, as well as air pollutant emissions, from cropland residue burning in Chhattisgarh for the last 21 years (2001–2021). The targeted major air pollutants include carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), and nitrogen oxides (NOx). This study uses primary data to calculate the percentage of residue burned in the fields, a parameter that has largely been calculated based on assumptions in many studies. The present study will be one of the first and most comprehensive analyses of agricultural residue burning and associated GHG emissions from the Central Indian region.

2. Materials and Methods

2.1. Study Area

The present study was conducted in the Chhattisgarh (C.G.) state of India. The state of Chhattisgarh encompasses a geographical area of 135,190 km^2, which lies between 17°46′ to 23°15′ N and 80°30′ to 84°23′ E (Figure 1). The state is bordered by seven states viz. to the northwest by Madhya Pradesh, to the north by Uttar Pradesh, to the northeast by Jharkhand, to the southeast by Orissa, to the south by Telangana and Andhra Pradesh, and to the southwest by Maharashtra. The main rivers of Chhattisgarh are Mahanadi, Indravati, and Hasdeo. In Chhattisgarh, approximately 80% of the population depends on agriculture, and 35% of the area of the state consists of agricultural land. Rice is the principal crop, and it is cultivated on about 3.4 million ha of land during the rainy season of each year. Because of the high production of rice, this state is known as the "*rice bowl*" of India. The state is mono-cropped and paddy-dominated, with more than 80% paddy cultivation during the Kharif season [33]. Chhattisgarh has a hot and humid tropical-type climate due to its proximity to the Tropic of Cancer. The annual maximum temperature varies between 30 °C and 45 °C during the summer, and the minimum temperature varies between 0 °C and 25 °C during the winter. The state has three distinct seasons: the winter season (November–February), the summer season (March–May), and the rainy season (June–October), and the state receives an average of 1292 mm of rainfall annually. The maximum rainfall occurs during August, followed by September. Based on the climatic zone, the state has been divided into three climatic zones: (1) Northern Hill, which is covered by mostly natural forest; (2) Bastar Plateau, which is also covered by forest (Southern Part); and (3) Chhattisgarh

Plains (Central Region), which is a prime agricultural landmark of Chhattisgarh. Approximately 90% of the agricultural areas of the state lie in Chhattisgarh Plains, and the crops depend on rainwater during the Kharif season. Due to the scarcity of irrigating water, farmers leave most of the cropland areas fallow during the Rabi season. Variation in the annual rainfall adversely affects crop harvesting time in this state.

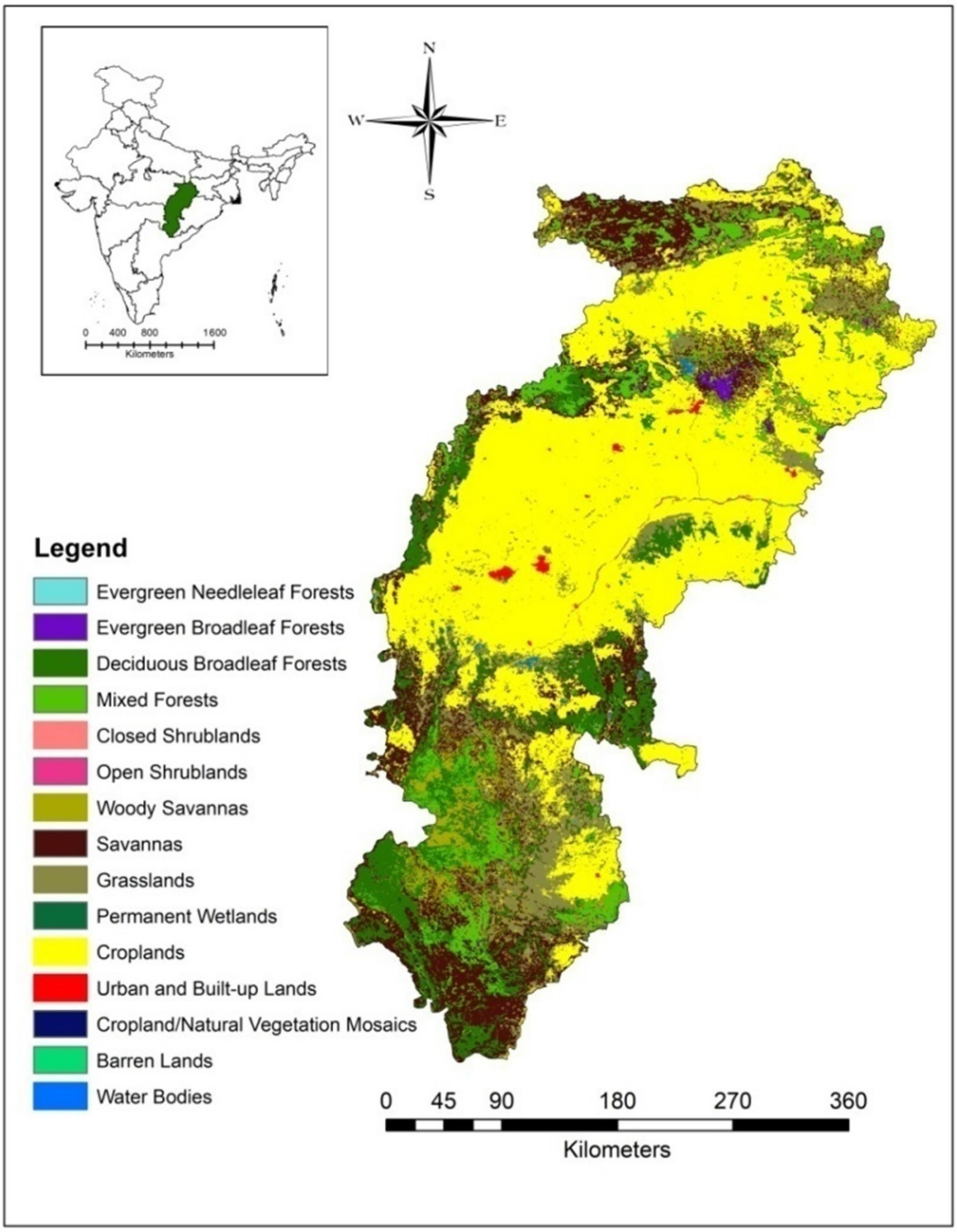

Figure 1. Location and land use land cover map of the study area.

2.2. Land Use Land Cover and Fire Data

This study employed active fire data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. We used data at 1 km resolution generated through the collection of 6 MODIS active fire products, based on the active fire detection algorithm [34] provided by Fire Information for Resource Management System (FIRMS). FIRMS is a global fire monitoring and alert system which delivers MODIS active fire points data and fire imagery to natural resource managers. The MODIS fire products (MOD14/MYD14) were downloaded from 1 January 2001 to 31 December 2021 for Chhattisgarh.

MODIS land use land cover data were collected from NASA Earthexplorer for the year 2019 at 500 m spatial resolution. The land use land cover (LULC) map of MODIS (MCD12Q1) was created using the supervised classification of MODIS reflectance data [35,36]. MCD12Q1 data, which were collected starting in 2001, are provided in tile format at the equator, using a sinusoidal grid in an HDf4 file format. The land use land cover map was extracted for the Chhattisgarh state using the boundary map. The total areas under different land cover classes are arranged in Table 1. The extracted map was overlaid with the MODIS active fire data from 1 January 2001 to 31 December 2021 to identify cropland fires across Chhattisgarh.

Table 1. MODIS-MCD12Q1-based total areas under different land use land cover classes in Chhattisgarh.

S. No.	Land Use Land Cover Class	Area (km^2)	Area (%)
1	Evergreen Needleleaf Forests (ENF)	1.72	0.00
2	Evergreen Broadleaf Forests (EBF)	507.45	0.38
3	Deciduous Broadleaf Forests (DBF)	16,146.63	12.00
4	Mixed Forests (MF)	9498.86	7.06
5	Closed Shrublands (CS)	0.22	0.00
6	Open Shrublands (OS)	62.90	0.05
7	Woody Savannas (WS)	5896.89	4.38
8	Savannas (SA)	19,303.40	14.34
9	Grasslands (GL)	17,840.07	13.25
10	Permanent Wetlands (PW)	63.32	0.05
11	Croplands (CL)	64,483.47	47.90
12	Urban and Built-up Lands (UBL)	466.24	0.35
13	Cropland/Natural Vegetation Mosaics (CNM)	115.06	0.09
14	Barren Lands (BL)	69.34	0.05
15	Water Bodies (WB)	156.06	0.12

2.3. Estimation of GHG Esimmions

Equation (1) is adapted for the estimation of crop residue burning [37,38]. The total emissions from crop residue are calculated as follows:

$$E_{Cr}\ (\mathrm{Gg/year}) = \Sigma\ \mathrm{crops}\ (P \times R \times D \times E \times B \times EF) \quad (1)$$

where E_{Cr} (Gg/year) = total emissions of the species in Gg; P = crop production during the specific year (Mt/Year); R = residue to crop production ratio; D = dry matter fraction; E = burning efficiency or fraction actually oxidized; B = percentage of dry matter burned in fields (%); EF = emission factor or grams of gas emitted per kg of dry matter residue burned in fields (g kg^{-1}).

Accordingly, the year-wise inventory of air pollutants, such as CO_2, CO, CH_4, N_2O, and NO_X emissions, from the crop residue burning was prepared for the years 2001 to 2021. The crop production data for various crops were collected from the Ministry of Agriculture and Farmers Welfare, Government of India. Wheat and rice production data were used in the analysis. The crop-specific production-to-residue ratio, dry matter fraction, and burning efficiency were calculated based on the values given by Ravindra et al. [37] (see Table 2).

Table 2. Type of crops and coefficients used for the preparation of crop residue burning emission inventory.

S. No.	Land Use Land Cover Class	Wheat	Rice
1	Residue to Crop Ration (R)	1.75	1.76
2	Dry Matter Fraction (D)	0.83	0.85
3	Dry Matter Burned in Fields % (B) [1]	0.03	0.001
4	Burn Efficiency (E)	0.86	0.89

[1] Calculated based on area burned in different years and crop production of Chhattisgarh State.

Emission factors are representative values that facilitate the estimation of gaseous emissions into the atmosphere. In this study, these factors were based on [12], and are presented in Table 3.

Table 3. Pollutants and their emission factors used in the study.

S. No.	Pollutant	Emission Factor g kg^{-1}
1	CO_2	1515
2	CO	92
3	CH_4	2.7
4	N_2O	0.07
5	NOx	2.5

2.4. Data Analysis

Initially, 15 classes of land use land cover type maps, derived from the MODIS Land Cover Type Product (MCD12Q1), were converted to vector files from the raster format using ArcGIS software (ArcGIS Pro 2.5, ESRI Inc. 2020, Redlands, CA, USA). Spatiotemporal pattern analyses were performed only for the cropland area in Chhattisgarh. The incidences of the MODIS active fire point layer were overlaid on the vector files of different vegetation maps, and the attribute information of points and polygons was joined, using an attribute table in ArcGIS to obtain the total number of fire points on the vegetation map. The extracted cropland area was overlaid with the active fire points for the generated vector file; after that, fire points falling within the cropland area were extracted using the ArcGIS tools. The point density module of the spatial analyst tool of ArcGIS was applied to analyze cropland fire spatial patterns using cropland fire point data [22]. Finally, with the help of this process, we prepared a map that exhibits cropland fire hotspot areas based on the point location and count of cropland fires in Chhattisgarh.

3. Results

3.1. Seasonal Variability of Fire

A total of 64,370 fire points were recorded in all land use land cover classes of Chhattisgarh, using MODIS active fire data from the last 21 years (2001 to 2021). The total number of fires was 709 in 2001, which increased to 3258 in 2021. The highest number of fires was found in 2017, followed by 2018, while the lowest number of fires was recorded in 2002. The total number of cropland fires showed an increasing trend between 2001 and 2021. The number of cropland fires in 2001 was 49, which increased to 1368 in 2021, with an average annual increase rate of 4.76% (Figure 2). The burned cropland area of the state also increased from 3.21 km^2 in 2001 to 72.98 km^2 in 2021. The highest burned areas were recorded in 2018 (284.42 km^2), followed by 2017 (248.14 km^2), and the lowest was recorded in 2002 (1.93 km^2).

Both the distribution of fire points and that of greenhouse gases emission were closely related to the area of the land cover type. As shown in Table 1, more than 47% of the land in Chhattisgarh is covered by cropland. Therefore, the relationships between land cover and fire counts were analyzed. Figure 3 shows the total fire counts in different land cover types. The results show that cropland areas were the single largest contributor to fire counts in the last 21 years, accounting for 32.37% (19,878) fire points, followed by Deciduous Broadleaf Forests (29.02%, 17,822 fire points), Mixed Forests (12.05%, 7404 fire points), Savannas (11.75%, 7218 fire points), Grasslands (7.27%, 4467 fire points), Woody Savannas (7.11%, 4369 fire points), Open Shrubland (0.23%, 145 fire points), Evergreen Broadleaf Forests (0.11%, 72 fire points), Barren Land (0.02%, 18 fire points), and Cropland/Natural Vegetation Mosaic (0.01%, 10 fire points).

A map of the spatial distribution of cropland fire (2001 to 2021) is presented in Figure 4. A high density of cropland fire was recorded in the central parts of Chhattisgarh, represented as the Chhattisgarh Plain region. The spatial distribution of fire for each year is represented in Figure 5. Results show that cropland fires accounted for 0.25% in 2001, which increased by approximately seven times, and reached 6.88% in 2021. Cropland fires gradually increased at an average annual rate of 4.76%. Figure 5 shows that the total cropland fires increased between 2001 and 2017, although the number of fire counts decreased in the period from 2018 to 2021. Fires were distributed unevenly. The maximum fire points for each year were recorded in the central region, which accounted for 89.6% of the total cropland fires, whereas the lowest numbers of fire points were recorded in the southern region (6.7%), followed by the northern region (3.6%). Figure 6 also shows the hotspots of cropland fires found in the central region of Chhattisgarh state.

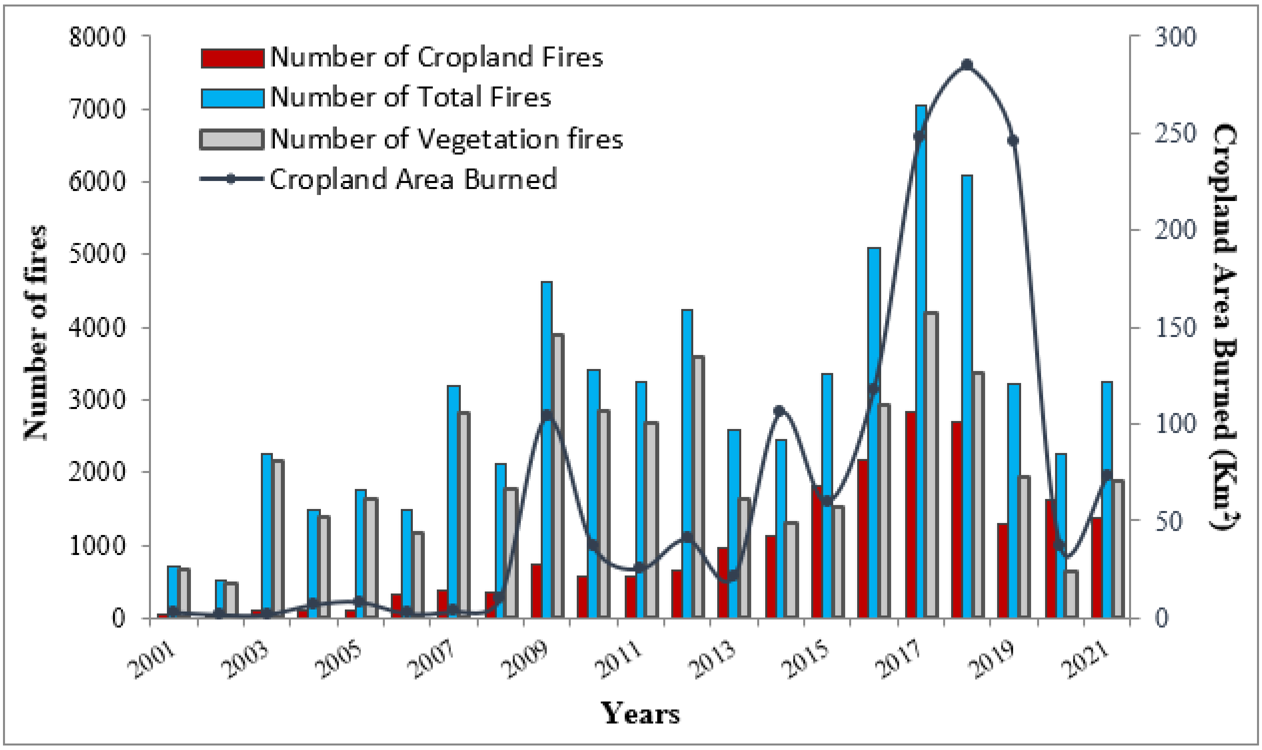

Figure 2. Annual cropland fires, vegetation fires, and burned cropland areas in Chhattisgarh between 2001 and 2021.

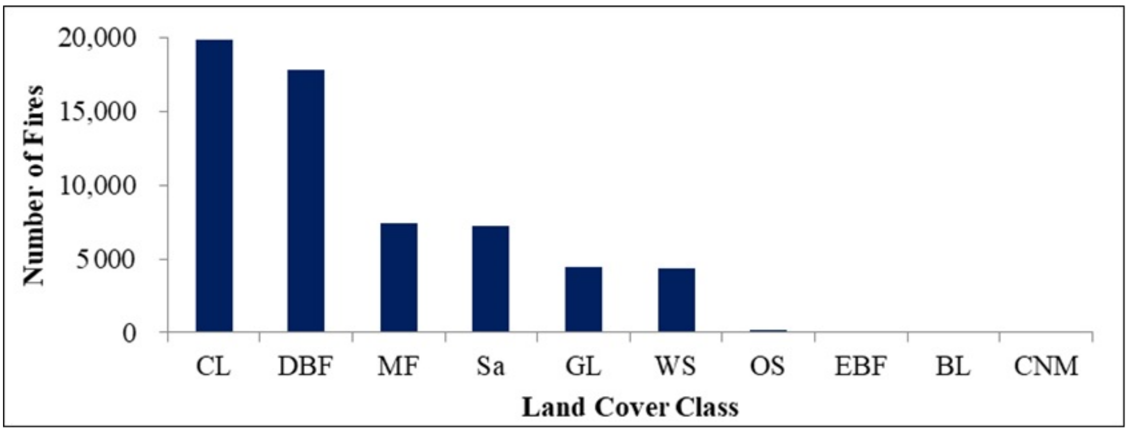

Figure 3. Fires in different land use land cover classes between 2001 and 2021. CL (Cropland), DBF (Deciduous Broadleaf Forest), MF (Mixed Forest), SA (Savannas), GL (Grassland), WS (Woody Savannas), OS (Open Shrubland), EBF (Evergreen Broadleaf Forest), BL (Barren Land), and CNM (Cropland/Natural Vegetation Mosaic).

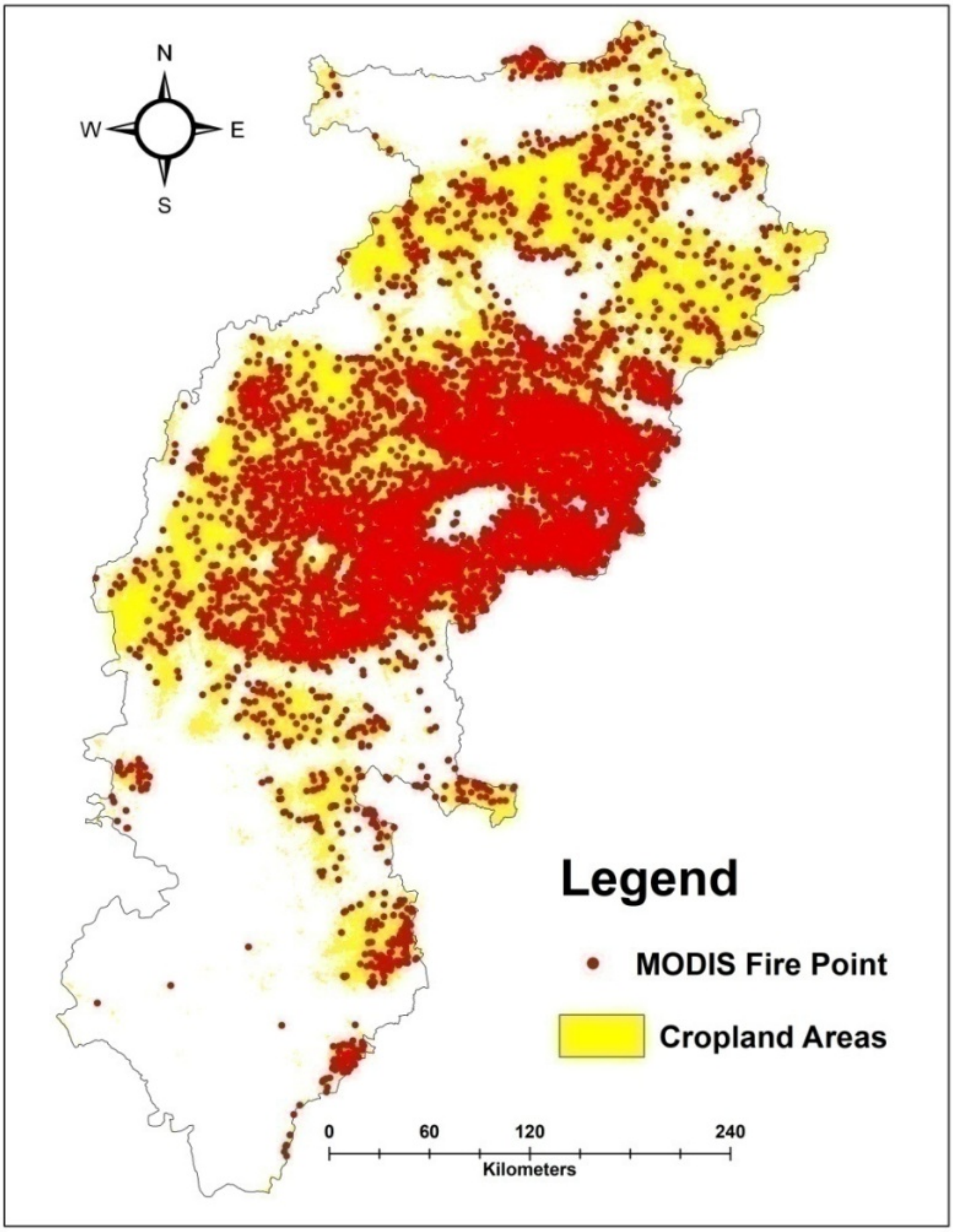

Figure 4. Cropland area and distribution of MODIS-derived cropland fire points between 2001 and 2021.

As shown in Figure 7, the monthly distribution of cropland fires also showed variability in Chhattisgarh. Our analysis suggested that the cropland residue burning peak was observed between December and March, with the highest number of fires in December (31.63%), followed by January (22.27%), March (15.97%), and February (13.70%).

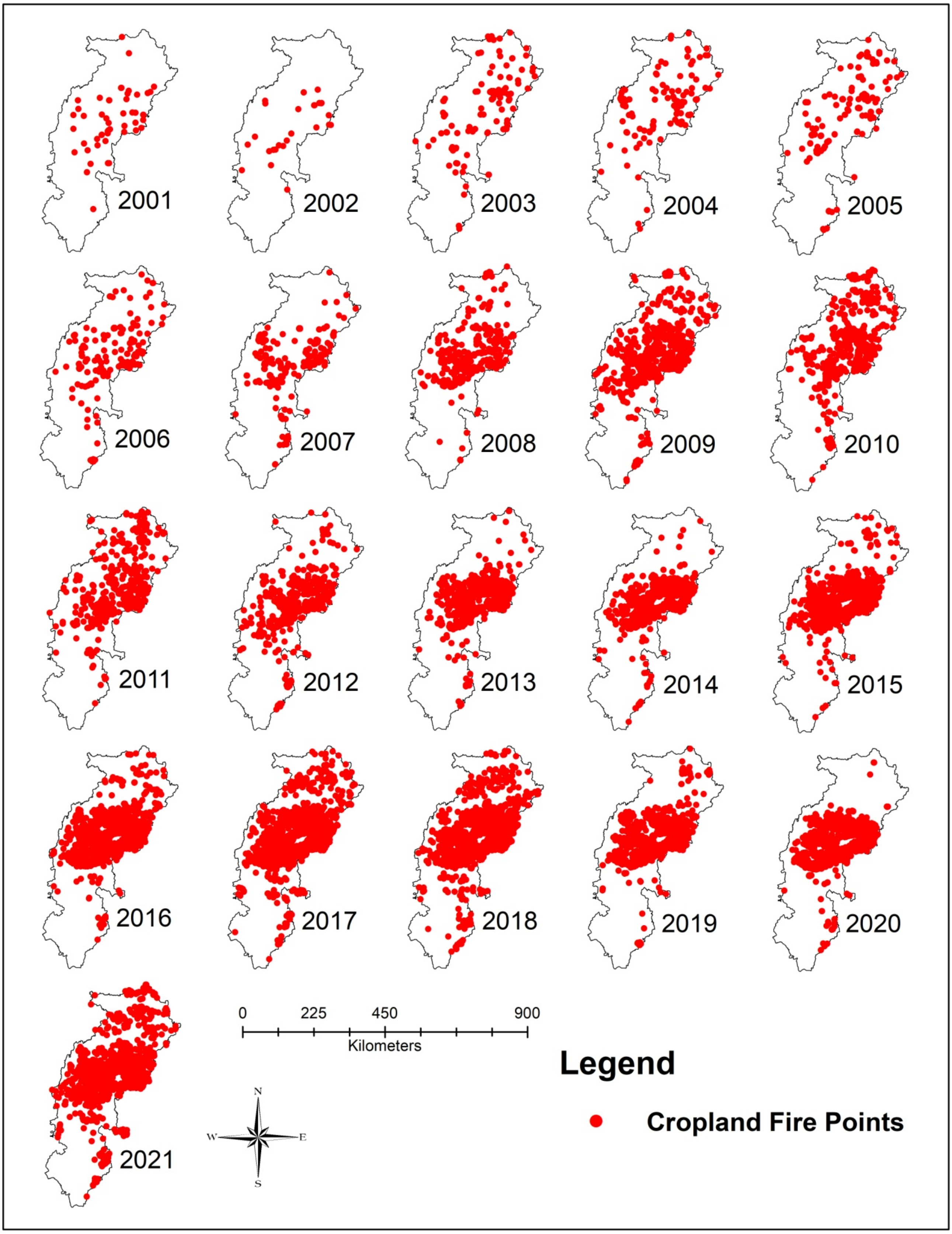

Figure 5. Spatial distribution of cropland fires between 2001 and 2021 in Chhattisgarh.

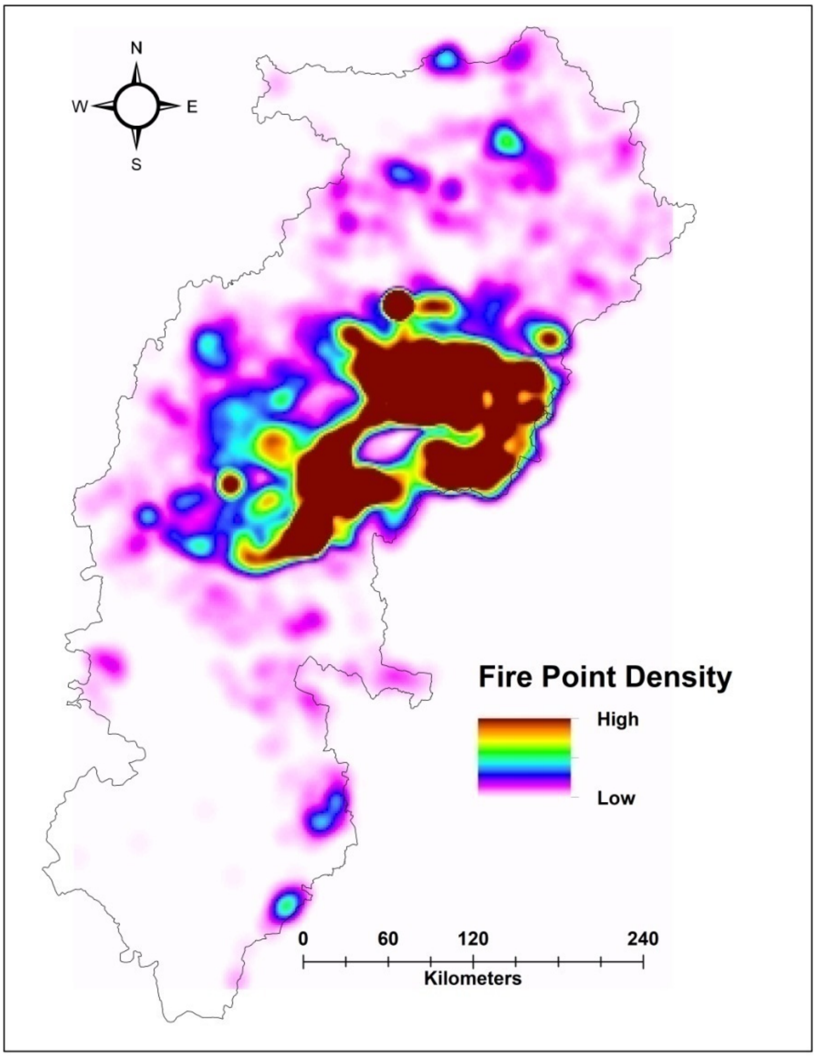

Figure 6. Kernel density estimation of MODIS-derived fire points for cropland over last 21 years in Chhattisgarh.

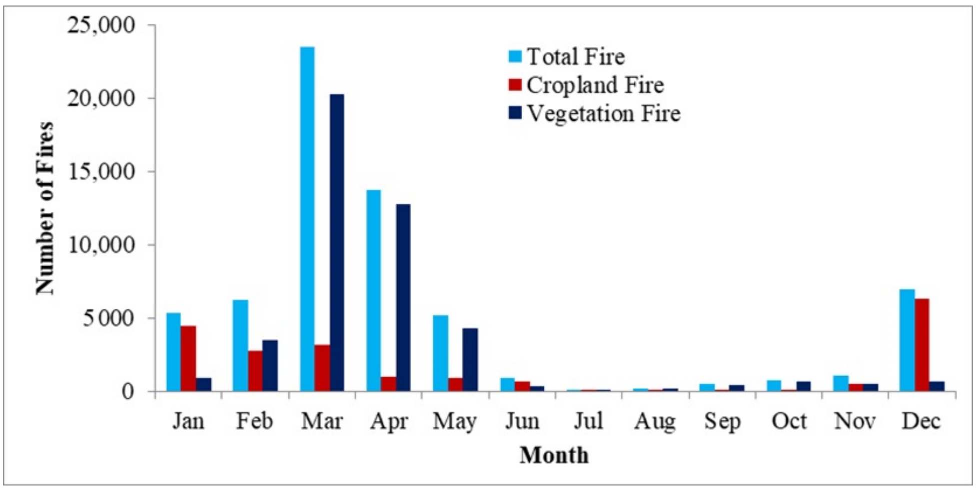

Figure 7. Distribution of month-wise cropland fires in Chhattisgarh between 2001 and 2021.

3.2. Emission of Greenhouse Gases

Tables 4 and 5 summarize the inter-annual variability in the production and emission of GHGs from two major cereal crops (wheat and rice) in Chhattisgarh over the last 21 years. The results indicate that production has increased from 79.50 Mt to 248 Mt for wheat and from 2369 Mt to 7161 Mt for rice. Similarly, the burned cropland area shows a rising trend, from 3.21 km^2 in 2001 to 72.98 km^2 in 2021.

Table 4. Emissions from wheat residue burning in Chhattisgarh state between 2001 and 2021.

Year	Production (Mt)	Emission (Gg/year)					Total
		CO_2	CO	CH_4	N_2O	NOx	
2000–01	80	396	24.1	0.71	0.02	0.65	422
2001–02	104	238	14.4	0.42	0.01	0.39	253
2002–03	99	238	14.4	0.42	0.01	0.39	253
2003–04	109	871	52.9	1.55	0.04	1.44	927
2004–05	82	1056	64.1	1.88	0.05	1.74	1124
2005–06	91	317	19.2	0.56	0.01	0.52	337
2006–07	92	449	27.3	0.80	0.02	0.74	478
2007–08	99	1215	73.8	2.16	0.06	2.00	1293
2008–09	93	1275	77.5	2.27	0.06	2.1	1357
2009–10	122	4568	277.4	8.14	0.21	7.54	4861
2010–11	127	3142	190.8	5.60	0.15	5.19	3344
2011–12	133	5017	304.7	8.94	0.23	8.28	5339
2012–13	141	2641	160.4	4.71	0.12	4.36	2810
2013–14	134	13,044	792.1	23.25	0.60	21.53	13,882
2014–15	135	7367	447.4	13.13	0.34	12.16	7840
2015–16	137	14,444	877.1	25.74	0.67	23.83	15,371
2016–17	160	30,524	1853.6	54.40	1.41	50.37	32,484
2017–18	131	34,987	2124.6	62.35	1.62	57.73	37,233
2018–19	163	30,234	1836.0	53.88	1.40	49.89	32,175
2019–20	116	4568	277.4	8.14	0.21	7.54	4861
2020–21	248	8978	545.2	16.00	0.41	14.81	9554
Total	2594	177,047	10,751.3	315.51	8.18	292.15	188,414

The estimated total emissions for the CO_2, CO, CH_4, N_2O, and NOx were found to be 177,046 Gg/year, 10,751 Gg/year, 315.51 Gg/year, 8.18 Gg/year, and 292.15 Gg/year, respectively (Table 4). Total emissions from rice residue burning for CO_2, CO, CH_4, N_2O, and NOx were 304,839 Gg/year, 18,511 Gg/year, 543 Gg/year, 14.09 Gg/year, and 503 Gg/year, respectively (Table 5). CO_2, CO, and CH_4 emissions from wheat residue burning increased almost by 22 times, from 396 Gg/year, 24.05 Gg/year, and 0.71 Gg/year, respectively, in 2000–2001, to 8978 Gg/year, 545 Gg/year, and 16 Gg/year, respectively, in 2020–2021. Emissions of N_2O and NOx from wheat increased by 20 times, from 0.02 Gg/year and 0.65 Gg/year, respectively, in 2000–2001, to 0.41 Gg/year and 14.81 Gg/year in 2020–2021. Similarly, in the case of rice residue burning, CO_2, CO, and CH_4 emissions also increased by approximately 22 times, from 682 Gg/year, 41.41 Gg/year, and 1.22 Gg/year, respectively, in 2000–2001, to 15,458 Gg/year, 939 Gg/year, and 27.55 Gg/year in 2020–2021. Emissions of N_2O and NOx increased by approximately 23 times, from 0.03 Gg/year and 1.13 Gg/year, respectively, in 2001, to 0.71 Gg/year and 25.51 Gg/year in 2021.

It is estimated that rice residue burning contributed to 324,411 Gg of GHGs (including CO_2 CO, CH_4, N_2O, and NOx), and wheat residue burning contributed to 188,414 Gg of GHGs in the last 21 years. For both wheat and rice, CO_2 accounted for 93.96% of the GHG emissions (by mass), and the rest was accounted for by CO, CH_4, N_2O, and NOx emissions. The annual GHG emissions from rice and wheat residue burning increased from 726 Gg/year and 421.51 Gg/year, respectively, in 2000–2001, to 16,450 Gg/year and 9554 Gg/year, respectively, in 2020–2021, with the emissions peak recorded in 2017–2018.

Table 5. Emissions from rice residue burning in Chhattisgarh state between 2001 and 2021.

Year	Production (Mt)	Emission (Gg/year)					Total
		CO_2	CO	CH_4	N_2O	NOx	
2000–01	2369	682	41	1.22	0.03	1.13	726
2001–02	5074	409	25	0.73	0.02	0.68	435
2002–03	2635	409	25	0.73	0.02	0.68	435
2003–04	5568	1500	91	2.67	0.07	2.48	1597
2004–05	4383	1819	110	3.24	0.08	3	1935
2005–06	5012	546	33	0.97	0.03	0.9	581
2006–07	5041	773	47	1.38	0.04	1.28	823
2007–08	5427	2091	127	3.73	0.1	3.45	2226
2008–09	4392	2196	133	3.9	0.1	3.6	2336
2009–10	4110	7865	478	14.02	0.36	12.98	8370
2010–11	6159	5410	329	9.64	0.25	8.93	5758
2011–12	6028	8638	525	15.39	0.4	14.25	9193
2012–13	6609	4546	276	8.1	0.21	7.5	4838
2013–14	6716	22,459	1364	40.03	1.04	37.06	23,901
2014–15	6021	12,685	770	22.61	0.59	20.93	13,499
2015–16	5789	24,869	1510	44.32	1.15	41.04	26,466
2016–17	8048	52,557	3192	93.67	2.43	86.73	55,931
2017–18	4931	60,240	3658	107.36	2.78	99.41	64,108
2018–19	6527	52,057	3161	92.77	2.41	85.9	55,399
2019–20	6775	7865	478	14.02	0.36	12.98	8370
2020–21	7161	15,458	939	27.55	0.71	25.51	16,450
Total	114,776	304,839	18,512	543	14.09	503	324,411

4. Discussion

Most of the fires detected by MODIS for Chhattisgarh occurred in cropland, followed by Deciduous Broadleaf Forests, Mixed Forests, Savannas, Grasslands, Woody Savannas, Open Shrubland, and Evergreen Broadleaf Forests. Fires varied with land use types and seasons. Over the 21-year study period in the state, there was an overall increase in both forest burning and cropland residue burning throughout the area. Results showed that crop residue burning increased 10- fold between 2001 and 2021. The highest fire count was recorded in the cropland area, which could be partially attributable to cropland's higher area (47.90%) as compared to other land classes in Chhattisgarh. Our result is similar to that of Verma et al. [22], who reported the highest (54.5%) level of residue burning in cropland during the period from 2002 to 2016 in Madhya Pradesh, which could be partially attributable to the comparably greater cropland area in Madhya Pradesh. Results suggest that the highest agricultural residue burning occurred in rice harvesting periods (Kharif season). Badarinath et al. (2009) and Kumar and Singh (2021) [9,20] also found that most of the cropland fires were associated with rice harvesting periods in Punjab.

Chhattisgarh Plains region is the main cropland area in the state, accounting for approximately 60% of the cropland area, whereas Bastar Plateau and Northern Hill are covered mostly by forests and hilly areas. Therefore, our results showed that the highest numbers of fire points were recorded in the Chhattisgarh Plains region. The lowest numbers of fire points were recorded in Bastar Plateau and Northern Hill, which could be partially attributable to the smaller agricultural area [39].

Our results showed that most fires were found from December to January during the study period (2001–2021), which could partially change sowing and harvesting times in the rice field during the Kharif season in Chhattisgarh. Badarinath et al. (2009) [9] also found that the rice crop harvesting period was extended in Punjab. The MODIS active fire data showed that there were two months (December and January) that contributed to the highest percentages of fires recorded during the last 21 years. The highest proportion was in December (31.63%), followed by January (22.27%). The crop residue burning peak was consistent with the local sowing and harvesting time. However, Verma et al. (2019) [22]

reported two distinct peaks in cropland burning, first in April and second in November, in the fifteen-year study period of Madhya Pradesh. In our study, we observed that most of the fires were associated with rice (Kharif season) harvesting periods. Our results confirm the findings of Jain et al. (2014) [19], who reported that 80% of rice straw was burned in situ in the states of Haryana, Himachal Pradesh, and Punjab, while only 50% and 15% of rice straw was burned in Karnataka and Uttar Pradesh, respectively.

By the present estimates, CO_2 accounted for 93.96% of the total emissions. The rest (6.04%) accounted for CO, CH_4, N_2O, and NOx. A decrease in emissions was observed during 2001–2003, due to lower crop production caused by drought, while the increase in emissions during 2016–2019 was proportional to the increase in crop production and burned areas. This annual variation in GHG emissions is dependent on the quantity burnt in the respective areas. When compared to certain studies associated with earlier estimations in India, Jain et al. (2014) [19] estimated that emissions of CO_2 were 1110.69 Gg/year for 2008–2009, which accounted for more than 91% of the total emissions from crop residue burning in Chhattisgarh. However, in our study, we found that the actual CO_2 emissions were many times higher than this. This is likely because most studies use the percentage of dry matter burned as a very crude default factor: 25% for developing countries, and a much smaller share, possibly 10%, for the developed world. In this study, the percentage of dry matter burned in the field was calculated for individual years, based on monthly MODIS burned area datasets for all the months between 2001 and 2021 as well as annual production data for each crop.

The cropland fire issues that have affected Haryana, Punjab, and Madhya Pradesh have also spread to Chhattisgarh. First, the farmers adopted advanced machine techniques that were used to compensate for the labor shortage. At present, crop fields are switching to combined machine-harvesting techniques from hand-harvesting techniques. Fields where hand-harvesting techniques were used had crops which were typically cut slightly higher from the ground, thus having less amount of straw to potentially burn. The distribution of straw as a fine layer over the agricultural field through the combined machine-harvesting techniques is more difficult to collect after the harvest [40]. Thus, most farmers opt for burning as the quickest and most common solution to remove agricultural residues from the field.

We used the MODIS active fire product and burn area product in this study to analyze residue burning. One of the drawbacks of MODIS in identifying burning events is that it cannot detect small-scale fires. Additionally, MODIS data may be affected by cloud cover and smoke interference, making it difficult to accurately identify burning events. The resolution of MODIS data is also limited, making it difficult to accurately determine the source and location of burning events. Finally, MODIS data can be noisy, meaning that false-positive results may occur due to factors such as instrument noise or errors in the data.

The sources of uncertainties in the estimation of greenhouse gases from agriculture residue burning may include measurement errors, changes in burn size or duration, and errors in fuel combustion emissions. Measurement errors can arise from the lack of accurate emission factors for burning residues, resulting in inaccurate estimates of emissions. Errors in fuel combustion emission estimation can also cause uncertainty, due to differences in the type of biomass burned, combustion efficiency, and other factors. All of these sources of uncertainty can lead to inaccuracies in estimates of greenhouse gas emissions from agricultural residue burning, which can affect the results of studies. We attempted to compare our emission estimation with the GFED4 dataset [41] for the Kharif season of 2021, and found that our estimation was 54% higher.

5. Conclusions

Agricultural residue burning, analyzed during the period from 2001 to 2021 in the Chhattisgarh state, revealed that cropland fire points have increased from 49 in 2001 to 1368 in 2021, with an average annual rate of increase of 4.76%. Overall, 92.71% of the cropland fires were recorded in the region of Chhattisgarh Plains, whereas only 7.28% of fires were recorded in the Bastar Plateau and Northern Hill. Approximately 31.63% of fires were recorded in December, coinciding with the rice harvesting period. The estimated emissions of CO_2, CO, CH_4, N_2O, and NOx from wheat residue burning were found to be 177,046.73 Gg/year, 10,751.33 Gg/year, 315.51 Gg/year, 8.18 Gg/year, and 292.15 Gg/year, respectively while emissions from rice residue burning, estimated for CO_2, CO, CH_4, N_2O, and NOx, were found to 304,839.21 Gg/year, 18,511.68 Gg/year, 543.29 Gg/year, 14.09 Gg/year, and 503.06 Gg/year, respectively. Out of the total GHGs emission from both wheat and rice, CO_2 accounted for 93.96%.

This study, based on MODIS active fire data, provided a means to monitor cropland fire occurrence trends, as well as their impact on GHGs emissions. In summary, the results from this study highlight the fire distribution and fire hotspots regions, which could be useful for policy mitigation, proper management, and monitoring of cropland residue burning in Chhattisgarh. In addition, significant amounts of crop residue can be used for ethanol or energy production.

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