Monitoring of fire incidences in vegetation types and Protected Areas of India: Implications on carbon emissions

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Carbon emissions released from forest fires have been identified as an environmental issue in the context of global warming. This study provides data on spatial and temporal patterns of fire incidences, burnt area and carbon emissions covering natural vegetation types (forest, scrub and grassland) and Protected Areas of India. The total area affected by fire in the forest, scrub and grasslands have been estimated as 48765.45, 6540.97 and 1821.33 km², respectively, in 2014 using Resourcesat-2 AWiFS data. The total CO₂ emissions from fires of these vegetation types in India were estimated to be 98.11 Tg during 2014. The highest emissions were caused by dry deciduous forests, followed by moist deciduous forests. The fire season typically occurs in February, March, April and May in different parts of India. Monthly CO₂ emissions from fires for different vegetation types have been calculated for February, March, April and May and estimated as 2.26, 33.53, 32.15 and 30.17 Tg, respectively. Protected Areas represent 11.46% of the total natural vegetation cover of India. Analysis of fire occurrences over a 10-year period with two types of sensor data, i.e., AWiFS and MODIS, have found fires in 281 (out of 614) Protected Areas of India. About 16.78 Tg of CO₂ emissions were estimated in Protected Areas in 2014. The natural vegetation types of Protected Areas have contributed for burnt area of 17.3% and CO₂ emissions of 17.1% as compared to total natural vegetation burnt area and emissions in India in 2014. 9.4% of the total vegetation in the Protected Areas was burnt in 2014. Our results suggest that Protected Areas have to be considered for strict fire management as an effective strategy for mitigating climate change and biodiversity conservation.

1. Introduction

Forest fires are recognised as a major driver of the global change in terrestrial ecosystems (Rudel *et al.* 2005). Biomass burning is the second largest source of trace gases in the global atmosphere (Crutzen and Andreae 1990; Bond *et al.* 2004) and strongly influence climate change (Crutzen *et al.* 1979; Olson *et al.* 1983). Biomass burning releases large amounts of carbon and other trace gases such as carbon monoxide, methane, hydrocarbons, nitric oxide and nitrous oxide and particulates into the

atmosphere (Seiler and Crutzen 1980). Sandberg *et al.* (2002) estimated that fires account for approximately one-fifth of the total global CO₂ emissions. Mievell *et al.* (2010) estimated historical biomass burning emissions and found that until 1970 the emissions were about 7400 Tg CO₂ yr⁻¹, but currently it reached 9950 Tg CO₂ yr⁻¹. CO₂, CO, and CH₄ represent the largest mass of carbon emissions from biomass burning (Marufu *et al.* 2000).

India has a total geographic area of about 32,87,263 km² and is situated between latitudes 6°44'–35°30'N and longitudes 68°7'–97°25'E. The

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causes of forest fires are mostly anthropogenic – caused accidentally, negligently and intentionally. These may be in order to clear the land for shifting cultivation, to get flush the growth of grasses and *tendu* leaves, or may be caused by uncontrolled prescribed burning, throwing burning cigarettes/bidis, illicit felling, and tribal customs. Fuel consumption will be influenced by many conditions such as fire intensity, fire type, vegetation type and climatic condition (Aulair and Carter 1993). According to Forest Survey of India (1988), annually, an area of 1.99 Mha is affected by shifting cultivation, which is, in turn, responsible for the emission of 1.56 Mt C. About 85% of the total cultivation in the north-east region is under shifting cultivation (Singh and Singh 1987). Ranjan and Upadhyay (2002) reported that shifting cultivation has already affected 2.7 Mha of the land and each year 0.45 ha of land is cleared under shifting cultivation. Shifting cultivation practice has cleared 0.05 Mha of forest area every year in the north-eastern states of India, and totally, 17.22 Mt wood biomass and 10.69 Mt C was removed at the rate of 1.72 Mt and 1.07 Mt C yr⁻¹, respectively (Manhas *et al.* 2006).

Remotely sensed data can contribute to a cost-effective and time-saving method of specifying the location of fire, intensity of fire events and the extent of the burnt area (Chuvieco *et al.* 1999). Remote sensing data and Geographic Information System (GIS) could assist in developing a range of measures of conservation effectiveness. Roy (2003) discussed the use of GIS to assess the forest fire risk. Fire monitoring has been carried using a wide range of satellite sensors (Lentile *et al.* 2006). Global Fire Emissions Database, version 4 (GFEDv4) provides global estimates of monthly burnt area, emissions and fractional contributions of different fire types, daily/3-hourly fields for scaling the monthly emissions to higher temporal resolutions. Emission estimates were derived by combining the burnt area data with a revised version of the biogeochemical model, Carnegie-Ames-Stanford Approach (CASA-GFED) that estimates fuel loads and combustion completeness for each monthly time step. From November 2000 onwards, estimates were based on burnt area, active fire detections, and plant productivity (van der Werf *et al.* 2010). The study in Mediterranean Europe showed that the IRS AWiFS-based burnt area map has improved the delineation of burn scars in addition to a number of small burnt scars that were mapped but not detected on low-resolution sensor data (Sedano *et al.* 2012). Earlier studies have used various satellite systems such as Landsat TM, Landsat ETM+, AWiFS, LISS-III, ETM+, SPOT, BIRD, DMSP-OLS, GOES-10 & 12, AATSR, AVHRR and MODIS (Joseph *et al.* 2009).

The studies in India have utilised moderate resolution AWiFS and high resolution LISS III data (Kodandapani *et al.* 2004; Somashekar *et al.* 2008; Reddy *et al.* 2009, 2012, 2014; Sowmya and Somashekar 2010; Harikrishna and Reddy 2012; Sharma *et al.* 2012; Kodandapani 2013; Sudeesh and Reddy 2013; Saranya *et al.* 2014; Satish and Reddy 2016). Near real-time monitoring of active fires is being carried out by National Remote Sensing Centre and Forest Survey of India using coarse resolution MODIS sensor as a part of Indian Forest Fire Response and Assessment System (NRSA 2006).

The Protected Areas have long been viewed as a cornerstone of biodiversity conservation and this role is recognised in a globally agreed target to be achieved by 2020 (Clark *et al.* 2013). There is a little research comparing ecological degradation before and after the Protected Areas were notified (Liu *et al.* 2001). A large number of Protected Areas fail for a variety of reasons in effectively conserving species, habitats and landscapes (CBD 2004). The future outlook reveals that biodiversity remains under threat and substantial action needs to be undertaken (SCBD 2014). The evaluation of conservation effectiveness is the core of well-protected area management. Financial resources and political support for nature conservation are limited and halting ecosystem degradation remains a challenge (Schagner *et al.* 2016). Data on the conservation effectiveness of Protected Areas is inadequate and must be available for conservation planning.

The Protected Areas are constituted and governed by the provisions of the Wild Life (Protection) Act 1972, which has been amended from time to time, with the changing ground realities concerning wildlife crime control and Protected Areas management. Implementation of this Act is further complemented by other Acts, viz., Indian Forest Act 1927, Forest (Conservation) Act 1980, Environment (Protection) Act 1986, Biological Diversity Act 2002 and the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act 2006.

There are four categories of the protected areas, viz., national parks, sanctuaries, conservation reserves and community reserves. A sanctuary is an area that is of adequate ecological, faunal, floral, geomorphological, natural or zoological significance. The sanctuary is declared for the purpose of protecting, propagating or developing wildlife or its environment. Certain rights of people living inside the sanctuary could be permitted. The difference between a sanctuary and a national park mainly lies in the vesting of rights of people living inside. Unlike a sanctuary, where certain rights can be allowed, in a national park, no rights are allowed. No grazing of any livestock shall also be permitted

inside a national park, while in a sanctuary, the chief wildlife warden may regulate, control or prohibit it. Conservation reserves can be declared by the state governments in any area owned by the government, particularly, the areas adjacent to national parks and sanctuaries and those areas that link one Protected Area with another. Such declarations should be made after having consultations with the local communities. Conservation reserves are declared for the purpose of protecting landscapes, seascapes, flora and fauna and their habitat. Community reserves can be declared by the state government in any private or community land, not comprised within a national park, sanctuary or a conservation reserve, where an individual or a community has volunteered to conserve wildlife and its habitat. A network of 668 Protected Areas has been established, extending over 161,221.57 km² (4.90% of total geographic area), comprising 102 national parks, 515 wildlife sanctuaries, 47 conservation reserves and 4 community reserves (<http://moef.nic.in/>). The incidences of forest fires can be considered as an indicator for effective management of protected areas. The incidents of widespread forest fires in various Protected Areas have received much public concern in the recent past (Somashekar *et al.* 2008).

There are no comprehensive studies with respect to the burnt area, fire incidences, amount of biomass burnt and carbon emissions in natural vegetation types and the Protected Areas of India. The present work of estimating burnt area and carbon emissions from forest fires has been taken up in order to assess the amount of trace gases released in 2014, in India, as a baseline estimate based on AWiFS burnt area product. This study is attempted to produce a nation-wide spatial database on the distribution of fires in all vegetation types in the Protected Areas of India, using remotely sensed information from Resourcesat-2 Advanced Wide Field Sensor (AWiFS) and MODIS data in order to prioritise the management efforts for ecological conservation.

2. Materials and methods

2.1 Mapping of burnt area: 2014

The Indian Space Research Organisation's (ISRO) Polar Satellite Launch Vehicle (PSLV-C16) had placed India's satellite Resourcesat-2, on 20th April 2011 in orbit. Resourcesat-2 AWiFS data were acquired from National Remote Sensing Centre, Hyderabad. The AWiFS satellite sensor has a 56 m spatial resolution. AWiFS operates in four spectral bands in the green (0.52–0.59 μm), red (0.62–0.68 μm), Near IR (0.77–0.86 μm), and Short-Wave IR (1.55–1.70 μm). Its radiometric

resolution is 12 bits. It has a swath width of 740 km and a revisit period of 5 days. The usefulness of the SWIR band has long been recognised for monitoring forest fires (NRSA 2006). Since AWiFS sensor is able to cover wide areas (740 km swath) and provides high temporal frequency, it is highly useful in mapping and monitoring of forest fires. Historically, the predominant fire season represents the months of February, March, April and May in different parts of India. Multi-temporal Resourcesat-2 AWiFS satellite data covering February, March, April and May 2014 was used for mapping of burnt areas in natural vegetation types of India (Reddy *et al.* 2017). Maximum-likelihood algorithm in supervised classification method was used to extract forest burnt area pixels on the shortwave infrared composite image (band combination 4, 3, 2). Representative training sets were selected manually representing burnt and unburnt area pixels for supervised classification. Visual image interpretation technique was used to improve the classified burnt area map.

The preparation of the burnt area map from AWiFS data involves the use of two existing spatial databases. The land cover and forest type map of 2013 and forest canopy density map of 2013 at 56 m resolution prepared as part of national carbon project has been used to estimate burnt area in each category (figure 1). Forest cover has been categorised under two canopy density classes, i.e., dense forest with >40% tree crown closure and open forest with 10–40% tree crown closure. Digital classification methods have subjectivity to deal with multi-sensor data, which can lead to misinterpretation caused by radiometric resolution, environmental conditions at the time of acquisition, terrain shadow, phenological variations in forest types and limitations in computational algorithms. In addition to digital classification methods, conjunctive use of visual interpretation technique was used in view of field information to be incorporated in terms of context, association, pattern, tone, and texture to delineate different vegetation type and land cover classes (Reddy *et al.* 2015, 2016).

The random sample approach was followed in allocating the sample points based on the proportional contribution in terms of aerial extent for the forest burnt area. Accuracy assessment was performed on the classified forest burnt area map of 2014 on the basis of 500 GPS based ground control points collected during 2014. The overall classification accuracy achieved was 92.28%. The kappa statistic was 0.89. Comparison of the MODIS-derived fire products with AWiFS data has been carried out to analyse spatial agreement of fire locations. Forest fire incidences were calculated using NASA Fire Information for Resource Management

Figure 1. Forest type and land cover map of India (source: Reddy *et al.* 2015).

System data. There are 25,589 MODIS fire incidences based on >50% confidence level covering forests of India in 2014. The classified burnt area maps intersected with MODIS fire points revealed 49.11% of matching only. AWiFS based mapping has delineated 216,793 forest burnt area patches in India. Many moderate and large size forest burnt areas (>5 km²) mapped in the AWiFS

are missing in MODIS map. It proves the spatial resolution capability of AWiFS data over MODIS.

The study has estimated that tropical dry deciduous forests occupy 217,713 km², followed by 207,649 km² under tropical moist deciduous forests, 48,295 km² under tropical semi-evergreen forests and 47,192 km² under tropical wet evergreen forests (Reddy *et al.* 2015). The burnt map of

India has been evaluated by training area confusion matrix to obtain classification accuracy. The spatial data of 614 Protected Area boundaries were obtained from the Wildlife Institute of India, Dehradun.

2.2 Monitoring of fires: 2006–2015

To maintain long-term records of fires, coarse resolution active fire detection products from MODIS were used. MODIS is an instrument on board the polar-orbiting Terra and Aqua satellites, with a revisit cycle of 1 to 2 days. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north in the afternoon. The MODIS active fire product uses a contextual algorithm based on the strong emission of middle infrared radiation from fires, captured from MODIS 4 μm and 11 μm radiances (Giglio *et al.* 2010). The MODIS fire products were downloaded from NASA Fire Information for Resource Management System (FIRMS) data from January 2006 to December 2015. (<https://firms.modaps.eosdis.nasa.gov/download/request.php>). This product contains the geographic coordinates, bands 21 and 31 brightness temperature, fire radiative power, and detection confidence level for all Terra and Aqua MODIS fire pixels (Oliveras *et al.* 2014). In the spatial analysis, only fire location points with a brightness value of 320 K and confidence level more than 70% were retained. This was necessary as air temperature in India could reach up to 45–47°C (318–320 K) during hot summer days, in the period March–June (Srivastava and Garg 2013a). Fire location points of 2006–2015 were clipped with land cover and forest type map of India to estimate year-wise count of fire incidences (Reddy *et al.* 2015).

2.3 Estimation of carbon emissions

The burnt area of forest, scrub and grassland burning and related emissions are typically estimated from the area burnt, fuel load and combustion efficiency, along with appropriate emission factors. To calculate emissions, the burnt area observed in the India, for 2014, is taken into consideration. The parameters considered for the estimation of emissions are the amount of land area burnt, the amount of fuel load (emission ratio), the burning efficiency and the emission factor for the gas (smoke) emitted.

CO₂ emissions were estimated following Seiler and Crutzen (1980) as:

$$\epsilon = A \times B \times \beta \times \text{EF},$$

where ϵ is the emissions (CO₂ in grams), A is the total land area burnt (m²), B is the average

biomass/fuel load (kg/dry matter/m²), β is the burning efficiency of above-ground biomass and EF is emission factor (mass of species per mass of dry matter burnt in g/kg).

Above-ground biomass density in Indian forests ranged from 12 to 230 Mg ha⁻¹ with a mean of 72.3 Mg ha⁻¹. The values 3.64, 4.0, 4.76, 3.52, 2.94 and 2.7 kg dry matter/m² for closed broadleaf deciduous forest, closed needle leaf evergreen forest, closed to open broadleaf evergreen-semi-deciduous forest, closed/open mixed broadleaf/needle leaf forests, mosaic forest/grassland/shrubland and open broadleaf deciduous forest, respectively, were adopted from Badarinath and Prasad (2011), who derived these values by averaging the dry matter values of different forest types. The study by Prasad *et al.* (2001) found 20–30% combustion factor for tropical secondary dry mixed forests during the initial phase of slash and burnt agriculture. Badarinath and Prasad (2011) have used combustion efficiency of 40% and expected that this value as a conservative estimate. Srivastava and Garg (2013b) have used combustion efficiencies of 25%, 85% and 95% for forest, scrub and grassland respectively. Venkataraman *et al.* (2006) have used combustion efficiencies of 48%, 50% and 41% for open, dense and very dense forest types, respectively. The emission factor (EF) is the ratio of carbon content of a carbonaceous gas and the carbon loss after burning (Levine 1991). In the present study, carbon emission factor values were derived from IPCC (2006) and Andreae and Merlet (2001). According to 2006 IPCC guidelines for National Greenhouse Gas Inventories, emission factor (g kg⁻¹) of CO₂ is 1643 in tropical forest and 1637 in temperate forest. According to a recent study by Akagi *et al.* (2011), the emission factor (g kg⁻¹) of CO₂ is 1580 in tropical forest and 1569 in temperate forest. The combustion efficiency of 40% for north-east India and 25% for the rest of India has been applied to estimate carbon emissions.

3. Results and discussion

3.1 Burnt area in 2014

The natural vegetation cover (forest, scrub and grassland) was estimated to be 965,128 km². It constitutes 29.36% of the total geographical area of India (Reddy *et al.* 2015). The total burnt area has been estimated as 57,127.75 km² in natural vegetation types. The burnt area of dry deciduous forest and moist deciduous forest are found as 26,634.40 km² (46.63%) and 18,717.95 km² (32.77%), respectively. The burnt areas of each vegetation type are shown in table 1. Of the total vegetation burnt area, 988.57 km² (1.73%) has

Table 1. *AWiFS-based burnt land area statistics across natural vegetation types in 2014.*

Vegetation type	Burnt area (km ²)	Burnt area (%)
I. Forest		
Tropical dense wet evergreen forest	643.05	1.13
Tropical open wet evergreen forest	8.50	0.01
Tropical dense semi-evergreen forest	1752.22	3.07
Tropical open semi-evergreen forest	91.09	0.16
Tropical dense moist deciduous forest	11137.24	19.50
Tropical open moist deciduous forest	7580.71	13.27
Tropical dense dry deciduous forest	15273.30	26.74
Tropical open dry deciduous forest	11361.10	19.89
Tropical dense dry evergreen forest	5.63	0.01
Tropical open dry evergreen forest	18.48	0.03
Tropical dense thorn forest	187.38	0.33
Tropical open thorn forest	474.52	0.83
Subtropical dense broad-leaved hill forest	142.02	0.25
Subtropical open broad-leaved hill forest	5.95	0.01
Subtropical dense pine forest	13.96	0.02
Subtropical open pine forest	26.14	0.05
Montane dense wet temperate forest	38.22	0.07
Montane open wet temperate forest	1.44	0.00
Himalayan dense moist temperate forest	4.49	0.01
Subtotal	48765.45	85.36
II. Scrub		0.00
Tropical dry scrub	6001.11	10.50
Tropical moist scrub	525.53	0.92
Subtropical scrub	14.33	0.03
Temperate scrub	0	0.00
Moist alpine scrub	0	0.00
Dry alpine scrub	0	0.00
Subtotal	6540.97	11.45
III. Grasslands	1821.33	3.19
Grand total	57127.75	100

been mapped in February, 19,061.68 km² (33.37%) in March, 19,227.55 km² (33.66%) in April and 17,849.95 km² (31.25%) in May. The burnt area under forests occupies 85.36% followed by scrub (11.45%) and grasslands (3.19%). Among total forest burnt area, open forests account for 26,520.08 km² (54.38%), followed by moderately dense forest with an area of 18,280.60 km² (37.49%) and very dense forest with 3964.77 km² (8.13%).

3.2 Monitoring of fires: 2006–2015

Overall, the state-wise decadal analysis indicates that Mizoram has the highest number of forest fire incidences, followed by Madhya Pradesh, Odisha, Assam, Chhattisgarh, Maharashtra, Manipur, Andhra Pradesh, Meghalaya, Nagaland, Tripura, Telangana, Arunachal Pradesh, Karnataka and Jharkhand. The dry deciduous forests of southern Chhattisgarh, eastern Maharashtra, southern Andhra Pradesh,

northern Telangana, eastern Karnataka and southern Jharkhand and moist deciduous forests of the whole of Manipur, Meghalaya, Nagaland, Tripura and southern Arunachal Pradesh are subjected to frequent fires. Year-wise count of forest fire incidences of India is given in figure 2. Year-wise count of forest fire incidences across states for the period 2006–2015 is given in table 2. Year-wise count of forest fire incidences across vegetation types for the period 2006–2015 is given in table 3. Forest fires were very severe in all vegetation types during 2009 and 2012. The seasonal temperature over India was above normal by 0.61°C, which makes the year 2012 the second warmest year since 1901 after the year 2009 (IMD 2009; <http://imdpune.gov.in/>).

3.3 Monthly CO₂ emissions in 2014

The burnt area under vegetation types has been extracted and emissions were calculated to determine

Figure 2. MODIS-based number of fire incidences in forests of India: 2006–2015.

Table 2. MODIS-based year-wise count of fire locations in states of India.

State	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Grand total
Andhra Pradesh	987	1497	1076	1506	986	1502	1537	1114	1558	916	12679
Arunachal Pradesh	834	833	533	948	452	466	730	677	671	506	6650
Assam	1949	1527	1460	2360	2022	1236	2423	1623	2480	1650	18730
Bihar	140	97	105	179	332	141	158	252	171	32	1607
Chhattisgarh	695	1874	1289	2776	2202	1941	2230	1181	837	951	15976
Goa	4	4	4	1	1	1	1	8	2	1	27
Gujarat	231	192	211	232	234	235	180	224	140	154	2033
Haryana	13	24	68	61	100	23	63	22	26	24	424
Himachal Pradesh	11	87	163	365	176	27	451	77	72	38	1467
Jammu & Kashmir	88	190	32	335	45	20	203	44	104	27	1088
Jharkhand	538	162	415	693	1284	389	243	467	219	339	4749
Karnataka	590	530	465	705	457	879	808	502	498	410	5844
Kerala	51	169	46	175	52	29	215	85	97	57	976
Madhya Pradesh	1108	1221	3084	3881	2265	2980	2868	877	622	393	19299
Maharashtra	1039	2077	1869	2687	1835	1870	3063	1708	1026	954	18128
Manipur	1989	1664	1426	1972	2037	1329	1720	1544	1846	1358	16885
Meghalaya	1603	1181	778	1347	1432	850	1069	827	1172	1306	11565
Mizoram	4750	3608	2141	4661	3905	1655	2360	2553	2176	2575	30384
Nagaland	1359	1128	776	1420	1481	1002	1220	1078	1082	929	11475
Odisha	1502	2266	1332	2365	2199	1296	2424	1894	1631	1188	18097
Punjab	65	43	204	89	90	38	137	84	70	36	856
Rajasthan	38	88	148	168	160	157	87	85	87	118	1136
Sikkim	17	0	0	1	3	3	4	2	6	1	37
Tamil Nadu	111	290	109	371	144	133	330	114	343	116	2061
Telangana	561	920	846	1327	598	635	1286	761	768	944	8646
Tripura	1767	1233	585	787	904	500	1110	559	972	469	8886
Uttar Pradesh	303	348	421	563	655	352	536	262	213	192	3845
Uttarakhand	114	199	664	710	484	65	896	83	327	205	3747
West Bengal	163	31	79	143	217	202	114	114	153	154	1370
Grand total	22620	23483	20329	32828	26752	19956	28466	18821	19369	16043	228667

the predominant fire season. From the observations, the months of March and April have shown high emissions in all vegetation types. Dense type of

forests were found to be emitting more CO₂ than the open type of forest due to the presence of high accumulation of flammable fuels in the form of litter

Table 3. MODIS-based year-wise count of forest fire incidences across vegetation types: 2006–2015.

Vegetation type	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Grand total
Dense dry deciduous forest	2074	3216	3773	5509	4006	4244	4539	2279	2335	1804	33779
Open dry deciduous forest	1534	1760	2470	3191	2556	2600	2778	1368	1263	1099	20619
Dense moist deciduous forest	4480	5287	4292	6833	5802	3812	6508	4217	4244	3089	48564
Open moist deciduous forest	5230	4816	3696	6040	5291	3316	5314	3752	4086	3326	44867
Dense thorn forest	7	13	9	5	51	21	17	8	7	10	148
Open thorn forest	31	52	51	57	55	47	60	31	42	28	454
Dense wet evergreen forest	2362	1819	1255	2398	2329	1096	1595	1539	1622	1657	17672
Open wet evergreen forest	16	25	8	24	21	10	14	15	12	10	155
Dense semi-evergreen forest	2668	2581	1584	3220	2408	1300	2262	1835	2073	1737	21668
Open semi-evergreen forest	289	250	148	318	248	130	171	161	196	208	2119
Dense dry evergreen forest	0	0	0	0	0	0	1	1	0	0	2
Open dry evergreen forest	0	1	2	1	0	0	0	1	1	0	6
Dense subtropical dry evergreen forest	0	0	0	2	0	1	5	0	0	0	8
Open subtropical dry evergreen forest	0	0	0	4	0	0	2	0	0	0	6
Dense subtropical pine forest	30	96	67	276	90	26	346	23	121	37	1112
Open subtropical pine forest	14	34	37	152	36	15	135	15	41	24	503
Dense himalayan moist temperate forest	31	21	21	152	49	15	99	32	30	21	471
Open himalayan moist temperate forest	2	6	6	28	8	6	17	4	6	4	87
Dense montane wet temperate forest	47	41	15	82	43	30	43	51	38	34	424
Open montane wet temperate forest	1	0	1	1	2	1	3	0	0	1	10
Dense subtropical broad-leaved forest	528	408	230	472	457	246	426	402	321	374	3864
Open subtropical broad-leaved forest	8	8	2	12	3	5	10	8	7	6	69
Dense montane dry temperate forest	1	10	0	7	4	1	5	8	2	3	41
Open montane dry temperate forest	4	10	3	2	2	0	3	1	1	1	27
Dense subalpine forest	3	3	1	3	2	3	1	1	1	2	20
Open subalpine forest	3	5	0	2	3	0	0	0	0	0	13
Subtotal	19363	20462	17671	28791	23466	16925	24354	15752	16449	13475	196708
Scrub	2927	2683	2355	3574	2869	2675	3646	2790	2621	2235	28375
Grassland	330	338	303	463	417	356	466	279	299	333	3584
Grand total	22620	23483	20329	32828	26752	19956	28466	18821	19369	16043	228667

Table 4. Temporal distribution of emissions of CO₂ (Tg) across density-wise vegetation types of India.

Vegetation type	February	March	April	May	Total
Dense dry deciduous forest	0.13	9.04	6.45	6.08	21.70
Open dry deciduous forest	0.32	4.44	2.5	4.92	12.18
Dense moist deciduous forest	0.07	3.84	8.26	4.79	16.96
Open moist deciduous forest	0.08	2.03	4.5	3.08	9.69
Dense wet evergreen forest	0.1	0.42	0.64	0.57	1.73
Open wet evergreen forest	0	0	0.01	0.01	0.02
Dense semi-evergreen forest	0.04	0.82	1.84	1.2	3.90
Open semi-evergreen forest	0.01	0.05	0.18	0.05	0.29
Dense thorn forest	0	0.08	0.04	0.08	0.20
Open thorn forest	0.01	0.22	0.05	0.23	0.51
Dense montane wet temperate forest	0	0.03	0.03	0.04	0.10
Dense subtropical broad-leaved forest	0.01	0.04	0.16	0.2	0.41
Open subtropical broad-leaved forest	0	0	0.01	0.01	0.02
Dense subtropical pine forest	0	0	0.02	0.02	0.04
Open subtropical pine forest	0	0	0.02	0.03	0.05
Open dry evergreen forest	0	0.02	0	0.01	0.03
Subtotal	0.77	21.03	24.71	21.32	67.83
Scrub	0.85	9.31	5.54	6.63	22.33
Grassland	0.64	3.19	1.9	2.22	7.95
Grand total	2.26	33.53	32.15	30.17	98.11

Figure 3. CO₂ (Tg) emissions from February to May months due to fires in India in 2014.

Table 5. Summary of trace gases emitted for India in Tg yr⁻¹.

Vegetation	CO ₂	CO	CH ₄	NO _x	N ₂ O	Total
Forest	67.83	4.47	0.29	0.01	0.07	72.67
Scrub	22.33	0.90	0.03	0.00	0.05	23.32
Grasslands	7.95	0.32	0.01	0.00	0.02	8.30
Grand total	98.11	5.69	0.33	0.01	0.14	104.29

and dry grass. Dense dry deciduous forest, open dry deciduous forest, dense moist deciduous forest, open moist deciduous forest, dense semi-evergreen forest, scrub and grassland are the major vegetation types contributing to a high amount of emissions. On a monthly basis, emissions were calculated to be as high at 9.04 Tg yr⁻¹ in dense dry deciduous forests during March 2014 (table 4). It has been observed that tropical dry deciduous forests are contributing high emissions of about 33.88 Tg yr⁻¹ followed by the tropical moist deciduous forests (26.65 Tg yr⁻¹), tropical semi-evergreen forests (4.19 Tg yr⁻¹) and tropical wet evergreen forests (1.73 Tg yr⁻¹). Among the non-forest types, tropical dry scrub and grassland were estimated with high emissions of 20.49 and 22.33 Tg yr⁻¹, respectively.

Emissions from forests were calculated as 0.77, 21.03, 24.71 and 21.32 Tg whereas scrub emitted 0.85, 9.31, 5.54, 6.63 Tg and grasslands 0.64, 3.19, 1.9 and 2.22 Tg during February, March, April and May, respectively. Fire incidences are more during March–May due to high temperature, air humidity and low fuel moisture, which contribute to increased emissions. Total emissions during these four months have been calculated as 2.26, 33.53, 32.15 and 30.17 Tg yr⁻¹ of CO₂ emissions (figure 3).

Estimation of carbon emissions in India reveals that about 98.11 Tg yr⁻¹ of CO₂ has been emitted due to fires. Among different forests, dry deciduous type of forest contributes about 50%, followed by the moist deciduous type of forest with 39.3% of CO₂ emissions. The amount of emissions of CO, CH₄, N₂O and NO_x released due to fires has also been calculated in the study. Emissions of other trace gases through forest fires, viz., CO, CH₄, N₂O, NO_x were estimated to be 5.69 Tg yr⁻¹ CO, 0.33 Tg yr⁻¹ CH₄, 0.01 Tg yr⁻¹ NO_x and 0.14 Tg yr⁻¹ N₂O (table 5). Venkataraman *et al.* (2006) have estimated an average of 10,101 km² of burnt area annually based on MODIS 2001–2003 data and reported the release of 49–100 CO₂ Tg yr⁻¹ from forest fires in India. The study by Badarinath and Prasad (2011) has used SPOT L3JRC product at a resolution of 1 km and estimated the release of 6.34 CO₂ Tg yr⁻¹ from forest fires. The study by Srivastava and Garg (2013b) has reported that CO₂ emissions for different forest types range from 74.95 to 123.84 Tg over five time periods (2003, 2005, 2007, 2009 and 2010).

3.4 Burnt area in Protected Areas: 2014

The natural vegetation cover in Protected Areas occupies an area of 110,596.89 km² and represents 11.46% of total natural vegetation cover of India. As per the natural vegetation database on 614 Protected Areas of India, forests occupy 82,757.98 km², followed by 14,205.99 km² of scrub and 13,632.92 km² of grasslands (Reddy *et al.* 2015). Of the 614 Protected Areas of India, 509 are occurring in Indian mainland (excluding Andaman &

Figure 4. Protected Area level forest burnt area map of India: 2014.

Nicobar Islands). Among the 509 Protected Areas, 195 (38.3%) were affected by fires in 2014 (figure 4). The burnt area is estimated as 9881.10 km², which occupies 9.5% of natural vegetation in Protected Areas of India. Burnt area under forests represents 8936.50 km² (90.4%), followed by 525.31 km² (5.3%) under scrub and 419.30 km² (4.2%) under grasslands.

Of the total vegetation burnt area in Protected Areas, 204.94 km² (2.07%) of area has been affected in February, 4554.36 km² (46.09%) in March, 3128.78 km² (31.66%) in April and 1993.01 km² (20.17%) in May (figure 5). It is clear that the spatial

distribution of forest fires is inconsistent across the Protected Areas. Area-wise, Nagarjunasagar–Srisailem Tiger Reserve has highest burnt area coverage (18%) among all of the Protected Areas, followed by the Gundla Brahmeswaram Wildlife Sanctuary (8.4%), Kaimur Wildlife Sanctuary (5.8%), Indravati Tiger Reserve (3.3%), Kaundinya Wildlife Sanctuary (3.3%) and Sri Venkateswara Wildlife Sanctuary (3.2%) (table 6). Based on percentage distribution of burnt area within individual Protected Areas, Debrigarh has the highest burnt area (80.6%) followed by Sarangarh–Gomardha, Karlapat, Baisipalli, Sunabeda, Koderma and

Figure 5. Distribution of monthly burnt area in Protected Areas of India in 2014.

Table 6. Protected Areas affected by large scale fires based on spatial extent of burnt area in 2014 (area in km²).

Sl. no.	Protected Area	State	Burnt area
1	Nagarjunasagar–Srisaillam	Andhra Pradesh	1778.02
2	Gundla Brahmeswaram	Andhra Pradesh	833.68
3	Kaimur	Bihar	570.29
4	Indravati	Chhattisgarh	330.62
5	Kaundinya	Andhra Pradesh	328.96
6	Sri Venkateswara	Andhra Pradesh	313.30
7	Sunabeda	Odisha	284.42
8	Bhimbandh	Bihar	279.57
9	Pakhal	Telangana	258.38
10	Debrigarh	Odisha	258.10

Table 7. Protected Areas affected by large scale fires with reference to total area in 2014 (area in km²).

Sl. no.	Protected Area	State	Burnt area/ total area (%)
1	Debrigarh	Odisha	80.6
2	Sarangarh-Gomardha	Chhattisgarh	55.8
3	Karlapat	Odisha	53.4
4	Baisipalli	Odisha	49.5
5	Sunabeda	Odisha	47.1
6	Koderma	Jharkhand	46.2
7	Bhimbandh	Bihar	42.6
8	Kaundinya	Andhra Pradesh	40.4
9	Pant (Rajgir)	Bihar	40.2
10	Udanti Wild Buffalo	Chhattisgarh	39.2

Bhimbandh (table 7). Somashekar *et al.* (2008) reported 4.46 km² of burnt area in the Bhadra Wildlife Sanctuary of Karnataka in 2004. In the present analysis, Bhadra Wildlife Sanctuary was affected by a burnt area of 23.91 km².

According to decadal scale fire incidences in Protected Areas, Nagarjunasagar–Srisaillam (Andhra Pradesh) has highest number of forest fire incidences, followed by Gundla Brahmeswaram (Andhra Pradesh), Indravati (Chhattisgarh),

Noradehi (Madhya Pradesh), Gumti (Tripura), Melghat (Maharashtra), Pakhal (Telangana), Sri Venkateswara (Andhra Pradesh), Ratapani (Madhya Pradesh), Eturnagaram (Telangana), Kothagarh (Odisha), Andhari (Maharashtra), Kawal (Telangana), Kaimur (Bihar) and Valmiki (Bihar).

3.5 Protected area-wise carbon emissions: 2014

Protected Areas contribute to 17.1% of CO₂ emissions in India, indicating the necessity of strict management policies for biodiversity conservation and climate change mitigation. The total estimation of emissions among Protected Areas for the forest, scrub and grassland represents 13.28, 1.75 and 1.74 Tg, respectively, in 2014 (figure 6). Nagarjunasagar–Srisailem was estimated to be a high emitter of CO₂ (2.0 Tg) followed by Gundla Brahmeswaram (0.94 Tg), Kaimur (0.71 Tg) and

Indravati (0.61 Tg), respectively (figure 7; table 8). Scrub and grasslands also contribute to high amounts of emissions due to fires in Protected Areas.

To prevent forest fires, the management of the Silent Valley National Park in Kerala has made special attention and is conducting awareness programmes. The formation of a buffer zone in the Silent Valley National Park has been an advantage which has resulted in effective control of the forests from fires (Satish and Reddy 2016).

Table 8. Analysis of top 20 Protected Areas based on descending order of carbon emissions in 2014 (Tg yr⁻¹).

Protected Area	Forest	Scrub	Grassland	Total
Nagarjunasagar–Srisailem	1.996	0.706	0.585	3.288
Gundla Brahmeswaram	0.943	0.118	0.000	1.061
Debrigarh	0.473	0.083	0.189	0.745
Kaimur	0.711	0.007	0.000	0.718
Manas	0.255	0.092	0.302	0.649
Indravati	0.619	0.005	0.000	0.624
Kaziranga	0.179	0.034	0.338	0.551
Sunabeda	0.395	0.135	0.002	0.532
Kaundinya	0.427	0.075	0.000	0.502
Sri Venkateswara	0.366	0.054	0.004	0.423
Bhimbandh	0.405	0.010	0.000	0.415
Peninsula Narsimha	0.307	0.071	0.000	0.378
Pakhal	0.364	0.008	0.000	0.372
Sarangarh-Gomardha	0.290	0.026	0.000	0.317
Baisipalli	0.276	0.008	0.000	0.284
Indira Gandhi (Annamalai)	0.238	0.014	0.010	0.262
Eturnagaram	0.243	0.003	0.000	0.246
Barnawapara	0.226	0.006	0.000	0.232
Cauvery	0.222	0.003	0.001	0.226
Sri Lankamalleswara	0.218	0.006	0.000	0.224

Figure 6. CO₂ emissions (Tg yr⁻¹) from Protected Areas of India: 2014.

Figure 7. Major CO₂ emissions from Protected Areas in 2014 (Tg yr⁻¹).

Operational fire monitoring using remote sensing data has become an activity of many governments and international agencies in response to concerns over the loss of forests and effects of burning on global atmosphere. There is a requirement of accurate and precise baseline data of forest fires in India and its deficiency in India were pointed out as background. The work by Joseph *et al.* (2009) reviewed the present policies and programs and emphasised the need to develop an adaptive fire management strategy in India.

4. Conclusions

The present study indicates that emissions due to forest fires are high in tropical deciduous forests as well as scrub and grasslands. The quantities of other trace gas (CO, CH₄, N₂O and NO_x) emissions are much lower than CO₂ emissions for different vegetation types. Integration of field data along with remote sensing based spatial information can be worked out for precise assessment of carbon stocks that helps in a better quantitative understanding of carbon emissions. The highest intensity and spread of forest fires observed in 2009, 2010 and 2012 were largely related to rise in temperatures. Policies focused on fire prevention must be considered with great care, including the use of prescribed fire to maintain fire regime in the ecosystems. The spatial database generated would be useful in studies related to the influence of fires on species regeneration and adaptability, ecological modelling and ecological damage assessment. The present study based on satellite-detected fire pixels is an excellent surrogate for anthropogenic disturbances and effectively useful in forest fire management in north-east India and mainly in Protected Areas, which have witnessed large-scale fires such as in Nagarjunasagar–Srisailem, Gundla Brahmeswaram, Kaimur and Indravati. To develop more practical policies for conservation effectiveness of Protected Areas, it is essential to integrate remotely sensed information with human population and socio-economics. The spatial data provided in this study can support to improve and prioritise management strategies in protected area monitoring in India. It is recommended to prepare fire maps for the past ten years using medium and high-resolution data to analyse the extent of forest burnt area and to predict fire-vulnerable forest ecosystems.

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