Nationwide assessment of forest burnt area in India using Resourcesat-2 AWiFS data

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This study provides application of Resourcesat-2 AWiFS satellite imagery for forest burnt area assessment in India. AWiFS datasets covering peak forest fire months of 2014 have been analysed. The total burnt area under vegetation cover (forest, scrub and grasslands) of India was estimated as 57,127.75 sq. km. In 2014, 7% of forest cover of India was affected by fires. Of the major forest types, dry deciduous forests are affected by the highest burnt area, followed by moist deciduous forests. Among the biogeographic zones, the highest forest burnt area was recorded in Deccan followed by North East and Western Ghats. The highest burnt area was recorded in Odisha followed by Andhra Pradesh, Maharashtra, Chhattisgarh, Tamil Nadu, Madhya Pradesh, Telangana, Jharkhand, Manipur and Karnataka. Spatial analysis shows that 232 grid cells in India have a burnt area greater than 20 sq. km. The database generated would be useful in ecological damage assessment, fire risk modelling, carbon emissions accounting and biodiversity conservation.

Keywords: AWiFS, forest fire, forest type, India, remote sensing.

BURNING of the world's biomass is a major source of trace gases and aerosol particles[1]. Globally, more than 350 m ha of forests were affected by fires in 2000 (ref. 2). Recurrent ground fires may be responsible for death of smaller trees, opening up canopy gaps[3]. Understanding of fire occurrence, extent and degree of damage is crucial for fire management and environmental studies[4]. The fires in Asia are mostly related to rise in temperature and decline in rainfall along with changes in land use[5]. The top-down factor that controls large fires is climate and the bottom-up factor is fuel. Fuel moisture and amount are contributions of climatic conditions[6], phenology, vegetation structure and species composition. In many tropical forests, frequent fires have a devastating long-term effect on vegetation structure and species composition[7].

India's CO_2 emissions in 2012 (about 6.8% of the world) make it one of the largest CO_2 emitting nations[8]. India has a policy of forest fire suppression, which dates back to the Indian Forest Act, 1927. According to this Act, setting of forest fires is a punishable offence. The Indian Forest Act made it mandatory for all forest-dependent officials to provide assistance in controlling fires. The National Forest Policy (1988) stresses forest protection against encroachment, grazing and fires. But, fires continue to be an annual phenomenon in Indian forests[9].

Ground fires in India destroy the organic matter needed to preserve an optimum level of soil humus and often adversely affects small trees and regeneration[10]. Management of forest fires is important in India where 55% of the forest cover is vulnerable to annual fires[11]. Anthropogenic activities, sometimes practised as part of management of grazing resources, collection of non-timber forest products, to clear land for shifting cultivation, to facilitate access by removing understorey vegetation, are all considered principal causes of fires. Historically, prescribed burning and limited fires are an integral part of forest ecosystems and essential for healthy growth and development of forests, depending on the type of species. These low intensity fires in the past kept the forest floor free from accumulation of litter, i.e. tree needles, dead grass, senescent leaves, twigs and dead trees. As a result, fires have also shaped vegetation patterns and wildlife distributions in the forests. Fire becomes a threat to fire-adapted ecosystems due to invasion by alien species or degradation. Many of the grasses are fire-adapted. The fern, *Pteridium aquilinum*, invasive shrub, *Lantana camara*, invasive tree species, *Acacia mearnsii*, are known for their fire adaptation[9]. However, large fires damage the forest in many ways because of increased intensity and frequency[12]. A recent study had reviewed the situation of forest fires in India[13]. Annually 6.34 Tg of CO_2 emissions have been estimated from forest biomass burning in India[14].

Remote sensing data allow interactive link with GIS and serve as a source of spatial information on global environment. Remote sensing assists in spatial and temporal fire detection. Burnt scars carry an impression of earlier burning events, usually measurable for up to three weeks following an incidence of fire[15]. Analysis of remote sensing can serve as a cost-effective and time-

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saving method for specifying the location of fire, fire events and the extent of the fire-affected area[16]. The utility of geographic information technology to assess fire vulnerability and degradation has been discussed by Roy[17]. Active fires can be noticed using thermal infrared bands (3.6–12 μm range) from coarse spatial resolution sensors such as Advanced Very High Resolution Radiometer (AVHRR), Along Track Scanning Radiometer (ATSR) or Moderate Resolution Imaging Spectroradiometer (MODIS). Lentile *et al.*[18] have summarized satellite sensors relevant to fire monitoring.

The most prominent information extraction techniques used for forest burnt area mapping are supervised classifiers, unsupervised classifiers, spectral thresholding, linear un-mixing and object-based classification[19]. In the case of coarse resolution (pixel size between 180 m and 1 km), burnt area pixels have a mixed signature with mean reflectance matching to unburnt ground coverage[20]. The work in Mediterranean Europe indicated that the IRS AWiFS based burnt area map improved the demarcation of burnt areas as well as detected a number of small burned scars that were not detected on MODIS and other low resolution sensor data[18]. Near real time monitoring of fires is carried out by National Remote Sensing Centre (NRSC) and Forest Survey of India (FSI) using MODIS sensor fire alerts on-board two of the satellites – Terra and Aqua[21]. The processed signals on forest fire hotspots are being transmitted to State Forest Departments during dry season[22].

A national level sample study at 1 : 1 M scale estimated that about 14,516 sq. km of forests were affected by fire during 1995 (ref. 23). The European Space Agency has assessed global forest burnt area using coarse resolution (1.1 sq. km) SPOT-VGT reported burnt area as 9% of the total forest area of India in 2000 (ref. 24). The study has monitored forest fires over India using Defence Meteorological Satellite Program–Operational Linescan System (DMSP-OLS) night-time satellite data from February to May 2005 (ref. 25). Coarse scale assessments do not reveal the realistic area figures and fail to map small scale burnt areas[26]. Other studies have utilized either coarse resolution data[27,28] or moderate to high resolution data, concentrated to certain states[26,29–31]; districts[32]; few protected areas of India[33–38]. However, there is no comprehensive nation-wide information available covering all the fire events in forests, scrub and grassland areas of India.

The present work attempts the first comprehensive nation-wide spatial database analysis of forest burnt areas of India for the year 2014. The study analyses spatial distribution of fires through multi-temporal advanced wide field sensor (AWiFS) data.

Study area

India has a geographical area of about 3,287,263 sq. km. It comprises 29 states and 7 union territories. The country has 21% of geographical area under forest cover[39]. There are 640 districts as per 2011 Census[40]. Rodgers and Panwar[41] have categorized India into 10 biogeographic zones based on topography, geography, land use and climate. Among the biogeographic zones, Western Ghats, Himalayas, North East India, and Islands (Andaman and Nicobar Islands) represent global biodiversity hotspots. There are 617 protected forest areas in India which include 102 national parks and 515 wildlife sanctuaries[42].

Materials and methods

Satellite data

Forest fires occur in India mainly between January and June. They are more frequent between February and May in different biogeographic zones of India. Multi-temporal Resourcesat-2 AWiFS satellite data covering February, March, April and May of 2014 were used for mapping the forest fires (Table 1).

Resourcesat-2 AWiFS datasets were procured from the National Remote Sensing Centre, Hyderabad. AWiFS satellite sensor has 56 m spatial resolution. AWiFS operates in four spectral bands: 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). Radiometric resolution is 12-bits. Revisit period is five days. 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 forest fires. Ortho-rectified Landsat ETM+ datasets were also downloaded from GLCF website[43]. Image-to-image registration of AWiFS images is carried out in relation to orthorectified Landsat ETM+ satellite data. To reduce the error due to atmospheric conditions, top-of-atmosphere reflectance programme was performed[44]. Two softwares, i.e. ERDAS Imagine and ArcGIS were used for digital image processing and GIS. Spatial administrative layers were used from the archive database of NRSC. Figure 1 shows elevation zone map of India with overlay of state boundaries.

Methods

The preparation of burnt area map from AWiFS data involves use of five existing spatial databases. (1) Land use map of 2013 at 56 m resolution prepared as part of national land use/land cover project[45]. (2) Forest type map of 2013 at 56 m resolution prepared as part of national carbon project[46]. (3) Forest cover map of 2009 at 24 m resolution developed by Forest Survey of India[39]. (4) Digital elevation model (DEM) from Shuttle Radar Topographic Mission (SRTM) with 90 m spatial resolution[47]. (5) MODIS-derived active fire locations for 2014 (https://earthdata.nasa.gov/data/near-real-time-data/firms/active-fire-data)[48].

First, all the non-vegetated areas (other than forest, scrub and grasslands) were extracted out in satellite imagery using spatial data of land use map. Short-wave IR, near IR, red spectral bands were assigned to highlight active fires. Smoke plumes and burnt areas can be better distinguished in the Short-Wave IR spectral channel (i.e. 1.55–1.70 μm), for detecting high temperature targets. SWIR channel is considered more suitable for identifying hotspots, since the maximum Planck black body radiance shifts to shorter wavelengths as temperature increases. The effectiveness of the SWIR band has long been documented for observing fires[21].

Table 1. Resourcesat-2 AWiFS data used for forest burnt area mapping

Path	Row	Date of pass
90	49	24 February 2014
94	48	20 February 2014
94	53	20 February 2014
95	63	01 February 2014
96	58	06 February 2014
101	54	07 February 2014
101	59	07 February 2014
101	64	07 February 2014
102	54	12 February 2014
104	60	22 February 2014
104	65	22 February 2014
107	53	13 February 2014
107	56	13 February 2014
113	54	19 February 2014
95	53	21 March 2014
95	63	21 March 2014
96	58	21 March 2014
100	49	22 March 2014
100	54	22 March 2014
100	59	22 March 2014
100	69	22 March 2014
105	55	23 March 2014
105	60	23 March 2014
106	56	28 March 2014
110	52	24 March 2014
111	58	05 March 2014
112	49	10 March 2014
112	54	10 March 2014
94	48	09 April 2014
94	53	09 April 2014
94	56	09 April 2014
99	49	10 April 2014
99	54	10 April 2014
99	59	10 April 2014
102	64	01 April 2014
102	67	01 April 2014
104	50	11 April 2014
105	60	21 April 2014
106	56	21 April 2014
109	52	12 April 2014
114	50	13 April 2014
114	55	13 April 2014
90	48	07 May 2014
90	53	07 May 2014
95	53	08 May 2014
96	58	13 May 2014
96	63	13 May 2014
98	54	23 May 2014
98	59	23 May 2014
101	59	14 May 2014
102	54	19 May 2014
102	64	19 May 2014
103	55	24 May 2014
103	60	24 May 2014
106	51	15 May 2014
106	56	15 May 2014
106	61	15 May 2014
111	53	16 May 2014

Image data of Resoursesat-2 AWiFS for December 2013 and January 2014 months do not have fire and are used for indication. Supervised classification was used to map forest burnt area pixels on shortwave infrared composite image (band combination 4, 3, 2). Representative training sets were selected manually representing burnt and unburnt area pixels. Maximum likelihood classifier was used for performing the supervised classification. The slope mask was generated from a SRTM digital elevation model. Potential shaded relief areas greater than 12° slope were mapped using normalized difference vegetation index and contextual information. On-screen visual interpretation technique was used to refine the classified burnt area maps. Post-classification smoothening was carried out with 3 × 3 matrix. Forest vegetation areas burnt in the different months of February, March, April and May 2014 were used to examine differences in fire occurrence across the forest, scrub and grasslands of

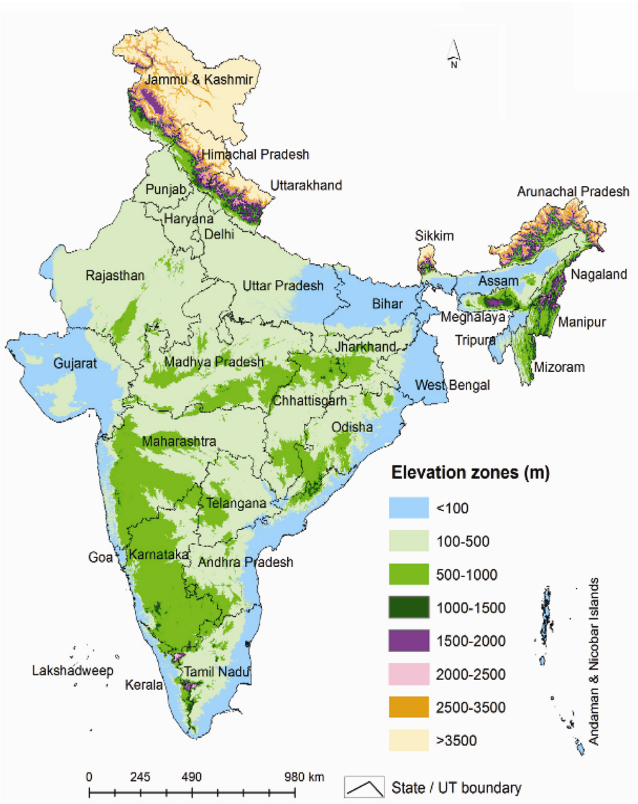

Figure 1. Map showing states and elevation zones of India.

India. The composite forest burnt area map was prepared using GIS spatial overlay from classified datasets pertaining to February, March, April and May 2014.

The present study considered various strata for analysing and conservation prioritization of forest burnt areas in India. Burnt area assessment was conducted with reference to forest types, forest canopy density, biogeographic zones, states, districts and elevation zones. A grid cell of 5 × 5 km was created to analyse the spatial distribution of forest burnt area. Forest type and land use/land cover map is given in Figure 2. Figure 3 shows outline of a flow chart that indicates the methodology of the study. Selected AWiFS image chips indicating burnt areas are shown in Figures 4–6.

Accuracy assessment

The burnt area map was evaluated by training area confusion matrix to obtain classification accuracy. The random sample technique was followed in assigning the ground control points to check the accuracy of forest burnt area. Five hundred randomly distributed ground control points were used in accuracy evaluation. Global database of MODIS fire locations were also used to compare AWiFS-based classified burnt area product.

Results and discussion

The total burnt area under natural vegetation cover of India was estimated as 57,127.75 sq. km with 216,793 patches in 2014 (Table 2). Temporal pattern in fires indicated a change in fire incidences with maximum forest fires in April and March followed by May. Forest fires in February are limited and highly scattered in distribution. Of the total burnt area, 988.57 sq. km (1.73%) was mapped in February, 19,061.68 sq. km (33.37%) in March, 19,227.55 sq. km (33.66%) in April and 17,849.95 sq. km (31.25%) in May (Figure 7). Burnt area under forests occupies 85.36% followed by scrub (11.45%) and grasslands (3.19%). Of the total fire-affected areas in forests, open forests represents 26,520.08 sq. km (54.38%), followed by moderately dense forest with an area of 18280.60 km^2 (37.49%) and very dense forest with 3964.77 sq. km (8.13%). At national level an area of 48765.45 sq. km (6.99%) of forest cover was affected by fires in 2014.

Spatial coverage across forest types

There was inconsistency in the proneness to fires across vegetation types. Among the fourteen forest types of India, dry deciduous forests show considerably high burnt area, followed by moist deciduous forests. The total fire-affected area of dry deciduous forest and moist deciduous forest is 26,634.40 sq. km and 18,717.95 sq. km respectively. Burnt area statistics across different types of forests, scrub and grasslands are given in Table 2. Among the 14 forest types, montane dry temperate forests, subtropical dry evergreen forests are found to be not affected by fire in 2014, may be due to inaccessibility, insufficient fuel loads and climatic conditions. Fires are limited in distribution in the montane wet temperate forests, Himalayan moist temperate forests and wet evergreen forests due to prevailing moisture and shade, including the moist litter on the floor. Fires in these forests are due to the spread of adjacent flammable vegetation or anthropogenic influences for shifting cultivation being practised in north eastern parts of India.

Most deciduous trees of India shed the leaves by end of January and fire occurrences are found during February to May, before the southwest monsoon sets in June. Dried grasses along with dry leaf litter are significantly high in dry deciduous forests. In teak-dominated deciduous forests, fire helps in the regeneration process of *Tectona grandis* (teak) but provides space for the invasive alien species[49]. The Himalayan pine forests, when fire is excluded, may result in poor regeneration. Here fire acts

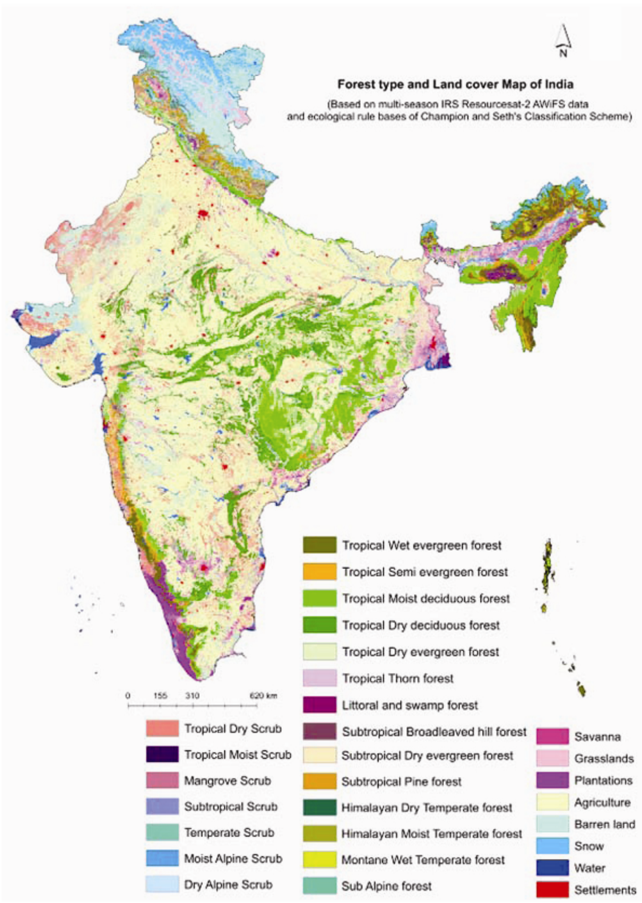

Figure 2. Forest type and land cover map of India.

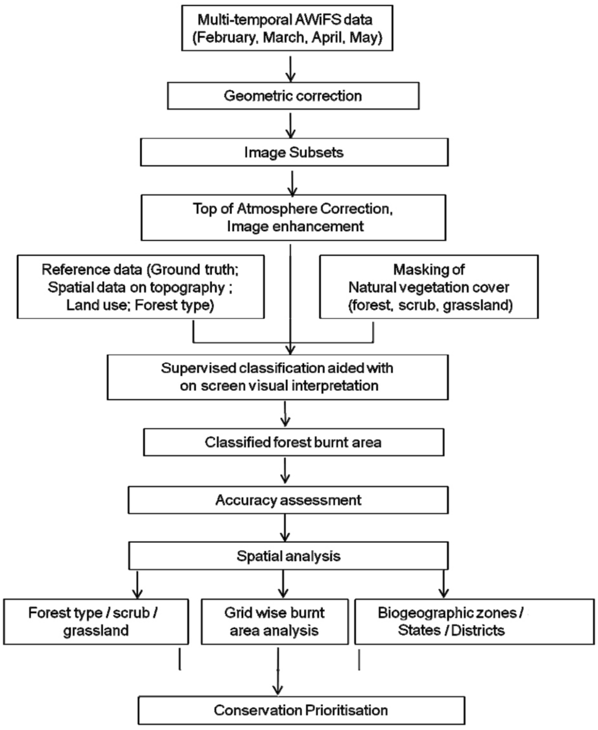

Figure 3. Flow chart of methodology.

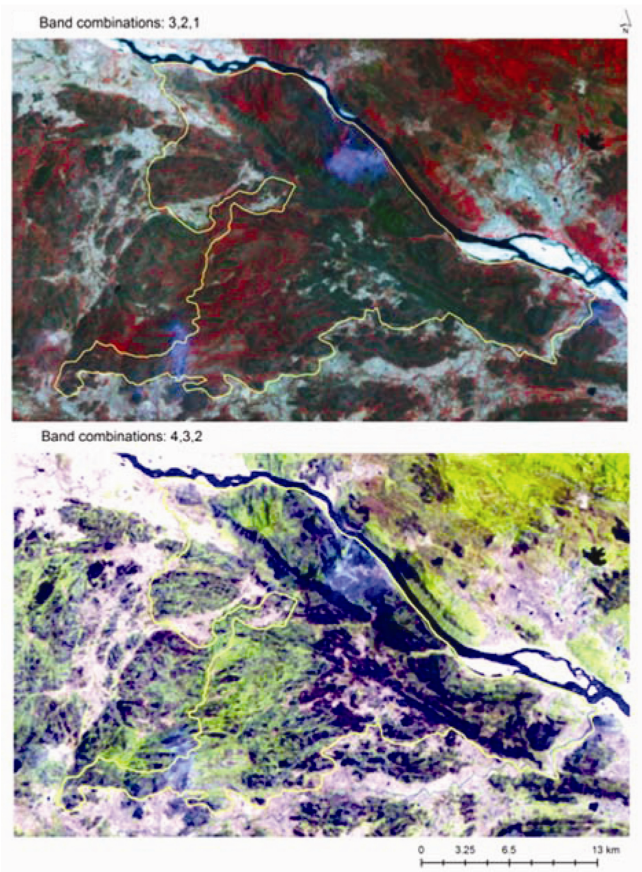

Figure 4. IRS Resourcesat-2 AWiFS image showing Baisipalli Wildlife Sanctuary, Odisha highlighting fire smoke plumes and post fire signatures in different band combinations (21 April 2014).

as a key driver in maintaining stand characteristics[7]. Fire frequency is high in pine forests which have more flammability due to resin content in trees[27].

The average maximum temperature for India as a whole was 33.13°C in 2014, which was 1°C higher than normal[50]. This was the third highest maximum temperature since 1971, the earlier two being in 2009 at 33.3°C and 1987 at 33.25°C. Maximum temperatures for most parts of India stayed higher by 1–2°C. It may have impacted on spread and intensity of fires in India during 2014. Fires were rigorous in different forests during 2009. The year 2009 was the warmest since 1901 (ref. 50). It had abnormal amount of fire incidences[51] and showed how climate can influence fuel moisture and thus fire. Studies carried out in Rajasthan[26] and Similipal Biosphere Reserve of Odisha[38] reported highest forest burnt area in 2009.

Spatial coverage across biogeographic zones

Temporal analysis across four dry months indicates that Deccan region was affected most by large number of fires in March (Figure 8). Eastern Himalaya, North East Coasts, and Gangetic plains were affected most by fires in April. Western Himalaya and semi-arid zones had comparatively more fire incidences in May. Amongst the biogeographic zones, Deccan represents the highest forest burnt area (79.01%) followed by North East (11.90%) and Western Ghats (4.42%). Comparative analysis for burnt area of scrub indicates that Deccan accounted for

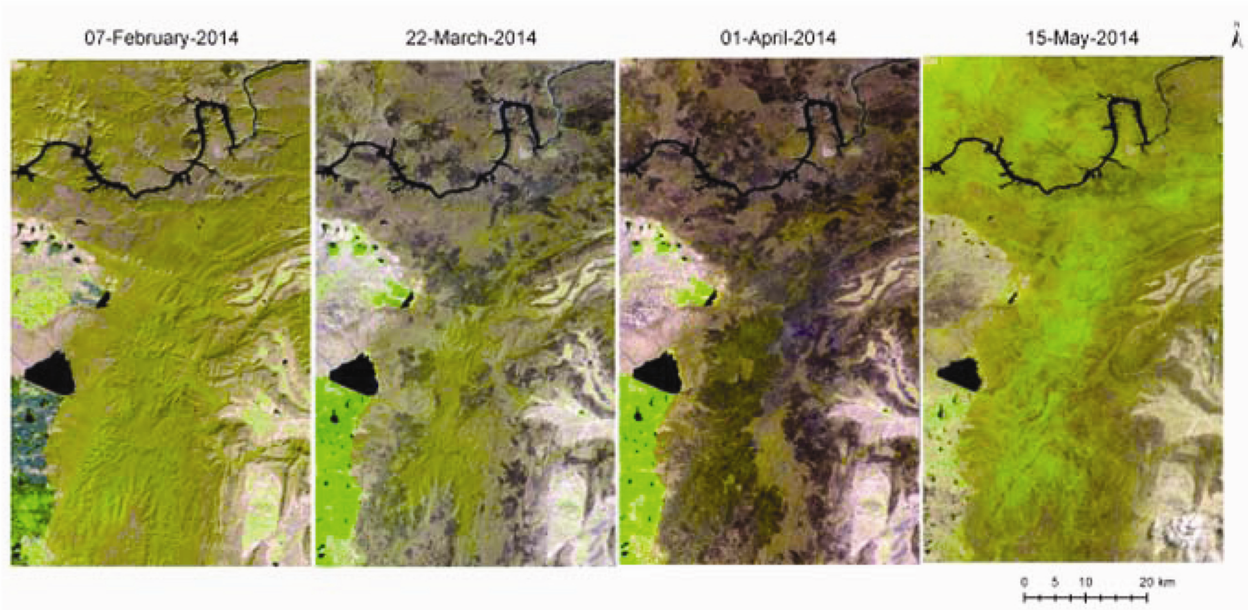

Figure 5. IRS Resourcesat-2 AWiFS images of part of Nallamalais (Andhra Pradesh and Telangana) (forest burnt area appears in deep purple and blackish brown tone).

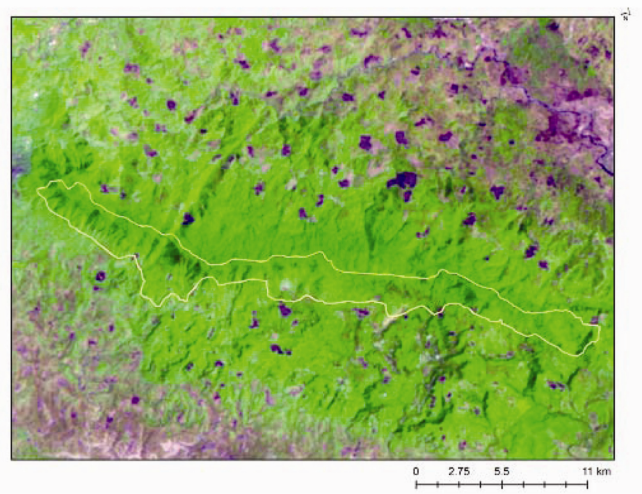

Figure 6. IRS Resourcesat-2 AWiFS image showing Nokrek National Park and surroundings, Meghalaya (21-April-2014): (forest burnt area appears in deep purple tone).

an area of 4600 sq. km, followed by North East (1108 sq. km) and Western Ghats (453 sq. km). Analysis for grasslands indicates that Deccan had 1334 sq. km of burnt area followed by north east (191 sq. km) and Western Ghats (174 sq. km). No forest fires were found in Trans-Himalayas and Islands due to prevalent climatic conditions and moist vegetation (Table 3). Forest fires are scanty in desert due to local people support and management effectiveness. Forest fires occurred mainly due to shifting cultivation in the North Eastern parts of India.

Table 2. Burnt area statistics across forest types, scrub and grassland

Type	Area (sq. km)	Percentage of area
Forest		
Tropical wet evergreen forest	651.55	1.14
Tropical semi evergreen forest	1843.31	3.23
Tropical moist deciduous forest	18717.95	32.77
Tropical dry deciduous forest	26634.40	46.62
Littoral and swamp forest	0.00	0.00
Tropical dry evergreen forest	24.12	0.04
Tropical thorn forest	661.90	1.16
Subtropical broad leaved hill forest	147.98	0.26
Subtropical pine forest	40.10	0.07
Subtropical dry evergreen forest	0.00	0.00
Montane wet temperate forest	39.65	0.07
Himalayan moist temperate forest	4.49	0.01
Himalayan dry temperate forest	0.00	0.00
Sub alpine forest	0.00	0.00
	48765.45	85.36
Scrub		
Tropical dry scrub	6001.11	10.50
Tropical moist scrub	525.53	0.92
Subtropical scrub	14.33	0.03
Temperate scrub	0.00	0.00
Moist alpine scrub	0.00	0.00
Dry alpine scrub	0.00	0.00
	6540.97	11.45
Grasslands	1821.33	3.19
Grand total	57127.75	100.00

Spatial coverage across states

Area-wise forest fire analysis indicates that the state of Odisha had more burnt area (Table 4). However with reference to total forest cover[52], Andhra Pradesh had the highest (25.43%) burnt area followed by Bihar, Tamil Nadu, Odisha and Telangana (Table 5). Fires have affected scrub in major parts of Andhra Pradesh, Maharashtra, Odisha, Madhya Pradesh and Manipur. Fires in grasslands show highest coverage of burnt area in Maharashtra and Odisha. Temporal variability of forest fires provides information on potential fire months in different states of India (Figure 9).

The fire-affected forest in Odisha has been estimated at 8513 sq. km in 2010 and 7424 sq. km in 2011 (ref. 31). In the present study, Odisha shows 8186.46 sq. km of forest burnt area in 2014. Rajasthan represents dry forests but the area affected by fires is low and varies between 2.7% and 10.9% from 2005 to 2010 (ref. 26). The total burnt area was assessed as 530.24 sq. km in 2005, 446.82 sq. km in 2006, 576.89 sq. km in 2007, 896.55 sq. km in 2008, 1998.37 sq. km in 2009 and 1448.16 sq. km in 2010 in Rajasthan[26]. In the present study, Rajasthan shows 392.82 sq. km of burnt area, lower than earlier estimates, indicating very effective conservation measures of the state forest department. Studies in Sikkim recorded a burnt area of 9.12 sq. km in 2009 (ref. 30). In the present study, the total burnt area in Sikkim was estimated as 6.78 sq. km.

The most important driver of deforestation in north eastern parts of India is the practice of shifting cultivation[53]. Forests are owned mostly by communities in the north east India. In Nagaland 91% of forest land is under the control of communities, followed by 90% in Meghalaya, 68% in Manipur, 62% in Arunachal Pradesh, 41% in Tripura and 33% in Mizoram and Assam[53]. Shifting cultivation affected 10 m ha of forests in the north eastern parts of India[54].

Of the 640 districts in India, 387 (60.47%) districts show forest fires (Figure 10). Forest burnt area of >1000 sq. km was recorded in 10 districts of India, i.e. Cuddapah, Prakasam, Chittoor and Kurnool of Andhra Pradesh, Gadchiroli of Maharashtra, Sambalpur of Odisha, Khammam of Telangana, Vellore and Dharmapuri of Tamil Nadu and Raipur of Chhattisgarh. Burnt area class of 500–1000 sq. km was distributed in 17 districts: Dantewara and Raigarh (Chhattisgarh), Rayagarh, Kalahandi, Kandhamal, Boudh, Nuapada, Bargarh, Angul (Odisha), Warangal, Mahabubnagar, and Adilabad (Telangana), Kohima (Nagaland), Tiruvannamalai (Tamil Nadu), Chamrajnagar (Karnataka) and Ukhrul and Churachandpur (Manipur).

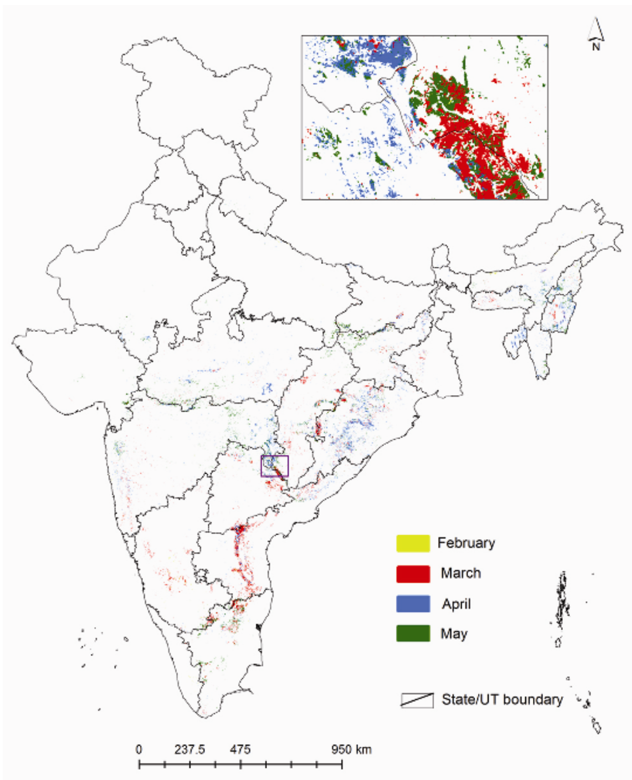

Figure 7. Classified forest burnt area map of India: 2014.

Analysis based on elevation zones

Burnt area analysis across elevation zones indicates that forest fires were concentrated mostly in the elevation range up to 500 m (64.76%), followed by range of 500–1000 m (30.14%). The high and very high elevation forests accounted for minor area under forest fires (Figure 11). It is evident that anthropogenic influences have a major responsibility in fire incidences in low and moderate elevation zones.

Grid-wise burnt area analysis

GIS analysis for distribution of fires indicates highest representation in grid class of 1–5 sq. km and <1 sq. km. Analysis indicates that 232 grids (1.31%) show burnt area >20 sq. km followed by 368 grids (2.08%) of 15–20 sq. km and 784 grids (4.43%) of 10–15 sq. km. These need conservation monitoring (Figure 12).

Accuracy assessment

Accuracy analysis was carried out on the basis of 500 GPS-based ground control points collected during 2014. The classification accuracy was computed as 91.46%. The kappa statistics is about 0.89. MODIS-derived fire products were compared with AWiFS data to analyse conformity of fire locations. Forest fire incidences were calculated using NASA's Fire Information for Resource Management System data. There were 25,589 MODIS fire incidences based on >50% confidence level covering forests of India. The burnt area classification maps of this study were compared with MODIS fire points.

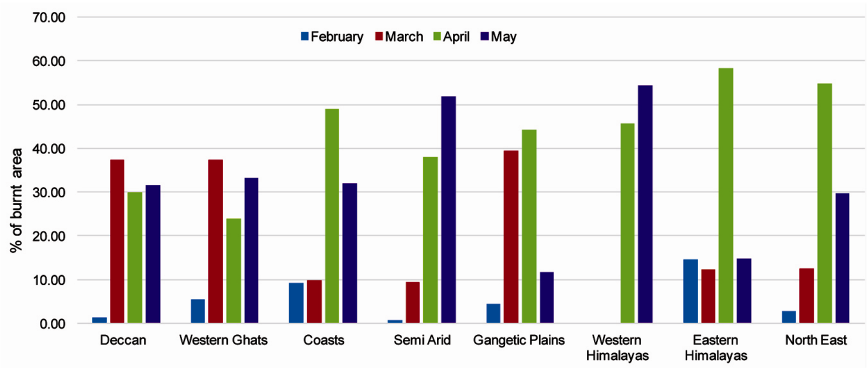

Figure 8. Temporal variability of forest fires in biogeographic zones.

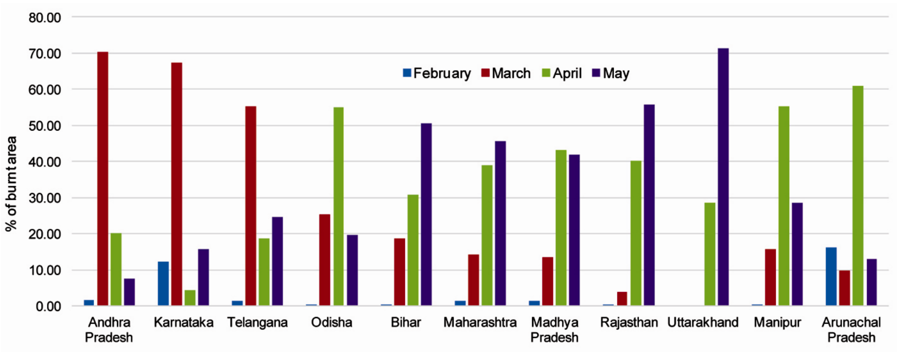

Figure 9. Temporal variability of forest fires in different states of India.

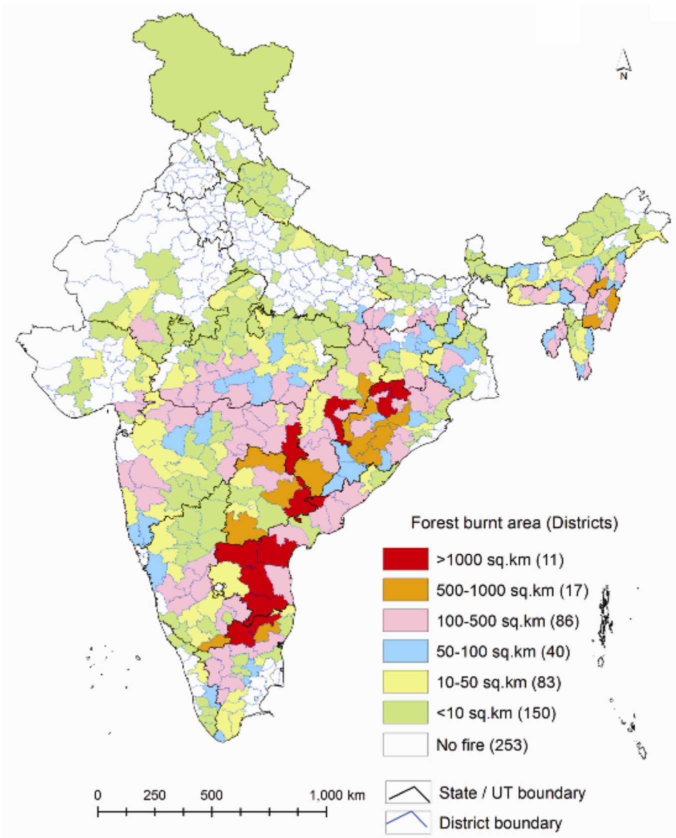

Figure 10. State/district level forest burnt area map of India: 2014.

Table 3. Biogeographic zone-wise spatial extent of burnt area (area in sq. km)

	Forest		Scrub		Grassland		Total burnt area	
Zone	Area	%	Area	%	Area	%	Area	%
Trans Himalayas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Western Himalayas	11.90	0.02	4.69	0.07	1.52	0.08	18.11	0.03
Eastern Himalayas	106.47	0.22	32.56	0.50	0.63	0.03	139.66	0.24
Gangetic Plains	587.03	1.20	68.19	1.04	80.67	4.43	735.88	1.29
Semi Arid	1456.08	2.99	263.01	4.02	34.12	1.87	1753.21	3.07
Desert	0.63	0.00	0.00	0.00	0.00	0.00	0.64	0.00
North East	5500.86	11.28	1108.14	16.94	191.30	10.50	6800.30	11.90
Deccan	39,199.44	80.38	4600.10	70.33	1334.68	73.28	45,134.22	79.01
Coasts	6.79	0.01	10.52	0.16	4.41	0.24	21.72	0.04
Western Ghats	1896.25	3.89	453.75	6.94	174.01	9.55	2524.01	4.42
Islands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grand total	48,765.45	100	6540.97	100	1821.33	100	57127.75	100

Table 4. State/UT-wise spatial extent of burnt area across forest, scrub and grassland (area in sq. km)

State/UT	Forest	Scrub	Grassland	Total
Andhra Pradesh	6611.86	1109.30	129.10	7850.26
Arunachal Pradesh	102.70	28.34	0.63	131.66
Assam	941.11	147.45	171.99	1260.55
Bihar	1773.22	39.17	0.89	1813.28
Chhattisgarh	4606.69	311.28	5.97	4923.95
Delhi	0.00	0.00	0.00	0.00
Goa	0.04	0.00	0.00	0.04
Gujarat	487.81	122.92	9.01	619.75
Haryana	1.84	0.43	2.16	4.43
Himachal Pradesh	0.91	0.61	0.33	1.85
Jammu and Kashmir	0.11	0.00	0.00	0.11
Jharkhand	2587.40	132.36	0.14	2719.90
Karnataka	1920.35	302.40	31.38	2254.12
Kerala	82.01	5.97	25.01	112.99
Madhya Pradesh	3342.66	593.43	27.60	3963.69
Maharashtra	5066.66	1030.61	746.67	6843.94
Manipur	1974.23	522.93	0.00	2497.16
Meghalaya	457.50	164.17	19.37	641.04
Mizoram	421.03	88.68	0.00	509.71
Nagaland	975.79	176.11	0.00	1151.90
Odisha	8186.46	964.42	351.22	9502.10
Punjab	0.85	0.15	0.00	1.00
Rajasthan	364.17	19.61	9.04	392.82
Sikkim	2.50	4.28	0.00	6.78
Tamil Nadu	4275.65	312.37	25.65	4613.68
Telangana	2955.23	359.83	178.85	3493.90
Tripura	739.00	10.74	0.00	749.74
Uttar Pradesh	459.07	45.32	58.24	562.63
Uttarakhand	42.01	8.53	6.49	57.04
West Bengal	386.37	38.90	21.58	446.86
Andaman and Nicobar	0.00	0.00	0.00	0.00
Chandigarh	0.00	0.00	0.00	0.00
Dadra and Nagar Haveli	0.23	0.61	0.00	0.84
Daman and Diu	0.00	0.00	0.00	0.00
Lakshadweep	0.00	0.00	0.00	0.00
Puducherry	0.00	0.04	0.00	0.04
Total	48765.45	6540.97	1821.33	57127.75

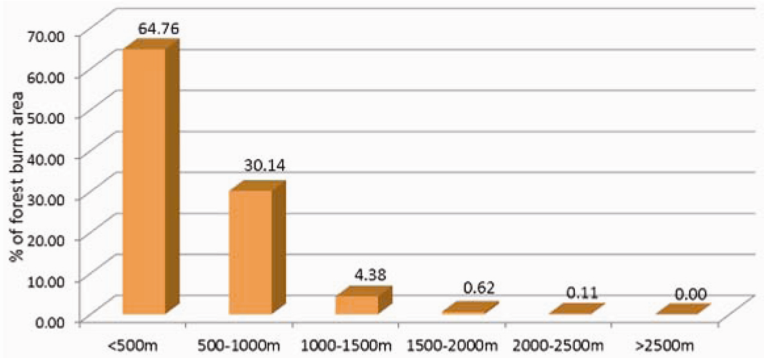

Figure 11. Distribution of forest burnt area across elevation zones.

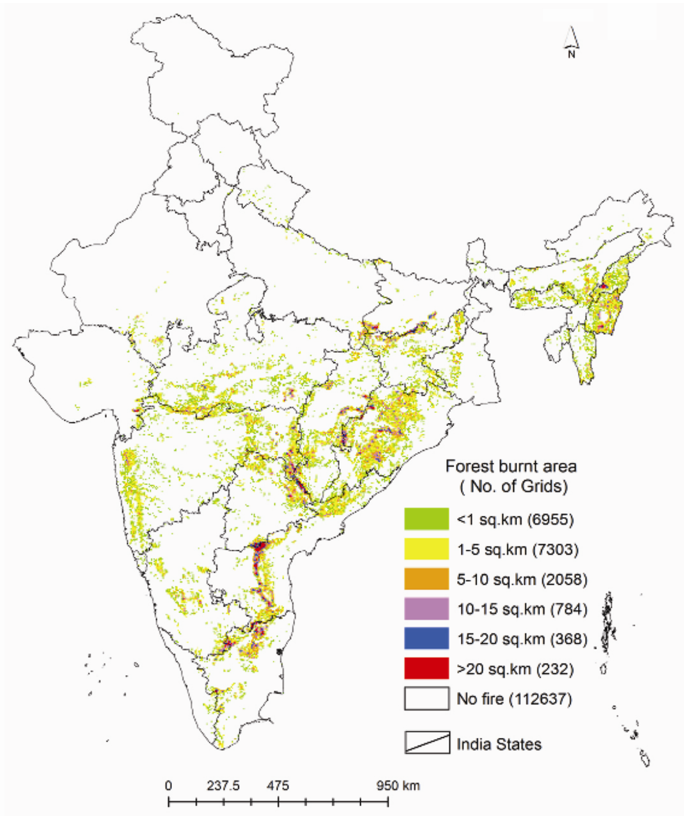

Figure 12. Grid-wise representation of forest burnt area in India.

The comparison reveals 49.11% of match. AWiFS-based mapping delineated 216,793 forest burnt area patches in India. Many moderate and large size forest burnt areas (>5 sq. km) mapped in the AWiFS were missing in MODIS map. It proves the capability of AWiFS data over MODIS.

Srivastava *et al.*[55] developed geospatial approach for fire likelihood based on various factors. Chuvieco *et al.*[56] prepared a spatial structure for fire risk assessment using geospatial techniques. Martínez *et al.*[57] rated human-caused wildfire risk for prevention planning in Spain. Prasad *et al.*[58] analysed biophysical and anthropogenic controls of forest fires in the Deccan Plateau of India. Vadrevu *et al.*[59] carried out fire risk appraisal using GIS techniques. The present work would be useful in studies related to ecological damage assessment, fire risk modelling, accounting trace gas emissions and biodiversity conservation[1,3,14,17,21,31].

Conclusions

This study has analysed and quantified forest burnt area in India using AWiFS data for the year 2014. It was evident that deciduous forests are highly prone to fires. It is

Table 5. State/Union Territory-wise analysis of percentage of forest burnt area (area in sq. km)

State/UT	Forest (FSI, 2013)	Forest burnt area (present study)	Burnt area (%)
Odisha	50,347	8186.46	16.26
Andhra Pradesh	25,999	6611.86	25.43
Maharashtra	50,632	5066.66	10.01
Chhattisgarh	55,621	4606.69	8.28
Tamil Nadu	23,844	4275.65	17.93
Madhya Pradesh	77,522	3342.66	4.31
Telangana	20,117	2955.23	14.69
Jharkhand	23,473	2587.40	11.02
Manipur	16,990	1974.23	11.62
Karnataka	36,132	1920.35	5.31
Bihar	7291	1773.22	24.32
Nagaland	13,044	975.79	7.48
Assam	27,671	941.11	3.40
Tripura	7866	739.00	9.39
Gujarat	14,653	487.81	3.33
Uttar Pradesh	14,349	459.07	3.20
Meghalaya	17,288	457.50	2.65
Mizoram	19,054	421.03	2.21
West Bengal	16,805	386.37	2.30
Rajasthan	16,086	364.17	2.26
Arunachal Pradesh	67,321	102.70	0.15
Kerala	17,922	82.01	0.46
Uttarakhand	24,508	42.01	0.17
Sikkim	3358	2.50	0.07
Haryana	1586	1.84	0.12
Himachal Pradesh	14,683	0.91	0.01
Punjab	1772	0.85	0.05
Dadra and Nagar Haveli	213	0.23	0.11
Jammu and Kashmir	22,538	0.11	0.0005
Goa	2219	0.04	0.00
Delhi	180	0.00	0.00
Andaman and Nicobar	6711	0.00	0.00
Chandigarh	17.26	0.00	0.00
Daman and Diu	9.27	0.00	0.00
Lakshadweep	27	0.00	0.00
Puducherry	50.06	0.00	0.00
	697,898	48,765.45	7.00

suggested that historical remote sensing data be used to prepare nationwide fire history maps for better formulation of forest fire control measures to minimize intensity and spread of fires.

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