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Emissions from open biomass burning in India: Integrating the inventory approach with high-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) active-fire and land cover data

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[1] Climatological mean estimates of forest burning and crop waste burning based on broad assumptions of the amounts burned have so far been used for India in global inventories. Here we estimate open biomass burning representative of 1995–2000 from forests using burned area and biomass density specific for Indian ecosystems and crop waste burning as a balance between generation and known uses as fuel and fodder. High-resolution satellite data of active fires and land cover classification from MODIS, both on a scale of 1 km × 1 km, were used to capture the seasonal variability of forest and crop waste burning and in conjunction with field reporting. Correspondence in satellite-detected fire cycles with harvest season was used to identify types crop waste burned in different regions. The fire season in forest areas was from February to May, and that in croplands varied with geographical location, with peaks in April and October, corresponding to the two major harvest seasons. Spatial variability in amount of forest biomass burned differed from corresponding forest fire counts with biomass burned being largest in central India but fire frequency being highest in the east-northeast. Unutilized crop waste and MODIS cropland fires were predominant in the western Indo-Gangetic plain. However, the amounts of unutilized crop waste in the four regions were not strictly proportional to the fire counts. Fraction crop waste burned in fields ranged from 18 to 30% on an all-India basis and had a strong regional variation. Open burning contributes importantly (about 25%) to black carbon, organic matter, and carbon monoxide emissions, a smaller amount (9–13%) to $PM_{2.5}$ (particulate mass in particles smaller than 2.5 micron diameter) and CO_2 emissions, and negligibly to SO_2 emissions (1%). However, it cannot explain a large “missing source” of BC or CO from India.

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1. Introduction

[2] Emissions from biomass burning have been investigated to understand their effects on the atmosphere and climate on a global scale [*Seiler and Crutzen*, 1980; *Levine*, 1991; *Hao and Liu*, 1994; *Liousse et al.*, 1996; *Olivier et al.*, 2001; *Yevich and Logan*, 2003; *Bond et al.*, 2004] and more recently on a regional scale, for example in Asia [*Streets et al.*, 2003a; *Reddy and Venkataraman*, 2002a]. Recent studies have separately treated the combustion of biofuels for residential cooking and heating, and restricted the definition of biomass burning to include forest and grassland fires of human and natural origin and the burning of agricultural or crop waste in fields [*Streets et al.*, 2003a; *Bond et al.*, 2004]. This definition is consistent with the different nature of emissions from shielded combustion of biofuel in small cooking fires and the open burning of forest and grassland biomass in large fires [*Venkataraman et al.*, 2005; *Bond et al.*, 2004], and is adopted in the present study.

[3] Forest and grassland burning and related emissions are typically estimated from the area burned, fuel load and combustion efficiency, along with appropriate emission

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factors. For India, bottom-up inventories [*Streets et al.*, 2003a; *Yevich and Logan*, 2003; *Lavoué et al.*, 2000; *Liousse et al.*, 1996] have so far used the climatological-mean estimates of *Hao and Liu* [1994] which reflect open burning in the mid-1970s, with the caveat that burning may not have changed much, with increases from population pressure balancing decreases from better land-management practices [*Streets et al.*, 2003a]. Global biomass burning data sets from satellite products like GBA-2000 [*Tansey et al.*, 2004; *Ito and Penner*, 2004] or GLOBSCAR [*Hoelzemann et al.*, 2004; *Simon et al.*, 2004], report a significant discrepancy in India, with GLOBSCAR [*Simon et al.*, 2004; *Hoelzemann et al.*, 2004] detecting only 16% of the GBA-2000 burned area in the year 2000 [*Simon et al.*, 2004]. Survey-based data sources include national estimates of forest and grassland burning [*Kaul*, 1993; *Kaul and Shah*, 1993; *Joshi*, 1991]. Recently available data include high-resolution forest cover and burned-area data from the *Forest Survey of India* [2001] and measurements and model estimates of biomass density for a variety of Indian forest ecosystems [*Haripriya*, 2000; *Chhabra et al.*, 2002]. In this work, we attempt to gain consistency among these data sources, specifically between forest categories in FSI reports and the MODIS/UMD data sets using the IGBP classification and available fuel loads estimated in global and India-specific studies, to reduce the uncertainty in Indian forest burning estimates.

[4] The inventory approach for agricultural or crop waste burning typically uses crop production, a crop-specific waste-to-grain ratio, dry matter fraction, combustion efficiency and the assumed fraction of the waste burned in the field [e.g. *Streets et al.*, 2003a], the last parameter being significantly uncertain for south Asia. In top-down estimates, GBA-2000 product estimated 3300 km^2 of cropland and grassland burned in India in the year 2000 [*Tansey et al.*, 2004]. However, the GLOBSCAR product excluded croplands from the burned-area product, because of an assumption that croplands were of unburnable nature or contained inadequate biomass [*Hoelzemann et al.*, 2004]. For India in particular, agricultural practices include field burning [*Ministry of Environment and Forests*, 2004], but continue to be highly uncertain [*Streets et al.*, 2003a], motivating an analysis in this study of crop waste generation [*Fertilizer Association of India*, 2001; *Koopmans and Koppejan*, 1997] and its use as animal fodder [*Amble et al.*, 1965; *Devendra and Sevilla*, 2002; *Ramachandra et al.*, 2000], thatching for rural homes [*Ravindranath and Hall*, 1995], residential fuel [*Habib et al.*, 2004] and industrial fuel [*Ravindranath and Hall*, 1995].

[5] Seasonal and interannual variability in open-burning emissions has been reported using active-fire-count data, [e.g*.*, *Duncan et al.*, 2003; *Reddy and Boucher*, 2004; *Generoso et al.*, 2003, *Streets et al.*, 2003a]. The recent availability of MODIS active fires [*Justice et al.*, 2002] and land cover classification [*Friedl et al.*, 2002] data offers the opportunity to have a direct high-resolution matching of fire-count and vegetation-cover at 1 km × 1 km resolution, as implemented in this work. Two satellite overpasses per day over India, with daytime and nighttime detection of fires, and the MODIS classification of low and high confidence fires allows a greater certainty in spatial and seasonal distribution of the emissions. We use the seasonal distribution of cropland fires in selected regions of India to evaluate assumptions in the bottom-up calculations of the types of crop waste burned in field and the duration of the burning periods. This paper describes the development of an open biomass burning database for India, not for a specific year, but representative of 1995–2000.

2. Inventory Estimates of Open Biomass Burning in India

2.1. Forest and Shrubland Burning

2.1.1. Forest and Shrubland Cover and Area Burned

[6] Forest cover data for 1999–2001, were obtained from *Forest Survey of India* (*FSI*) [2001], estimated from satellite sensors LISS-III (23.5 m × 23.5 m resolution) and IRS PAN (5.8 m × 5.8 m) on the IRS 1C/1D satellite, and thematic maps for 562 districts of India. FSI reports forest cover in three crown density classes of very dense (70–100%), dense (40–70%) and open (10–40%) forests. The FSI "very dense forests" correspond to the IGBP categories [*Loveland et al.*, 2000] of forest (60–100%) and "open and dense forests" to woodland and shrubland (10–60%). FSI forest cover data is subject to extensive ground-truth comparisons, using methodologies described by *FSI* [2001], which involve error matrix analysis using 2000 sampling units in each vegetation or land use class. The reported accuracy of the forest cover product is 85.2 to 99.6% in terms of incorrect inclusion and 89.7–98.4% for incorrect exclusion of pixels in each category.

[7] The mean forest cover between 1999 and 2001 was 416809 km^2 in "very dense" and "dense" forests, and 258730 km^2 of "open" forest in India, totaling 675539 km^2 [*FSI*, 2001]. These "very dense" forests are found in the northern and northeastern states of Jammu and Kashmir, Arunachal Pradesh, Assam, Himachal Pradesh and Sikkim, the southern state of Kerala and the union territory of Andaman and Nicobar islands. A total of the reported "dense" forests in these seven states results in an estimated 112,795 km^2 of "very dense" forests in India. In this study we use the high-resolution 1 km × 1 km vegetation cover data from MODIS [*Friedl et al.*, 2002] (please see auxiliary material[1] Figure S1). Also shown are selected regions, western Indo-Gangetic plain, east and northeast, central and south India, with similar agricultural practices and land use, in which an analysis of the spatial and seasonal distribution of fires was made.

[8] Change in the resolution of satellite forest mapping, and in classification of some areas as dense and open forest during 1999–2000 [*FSI*, 2001], did not permit calculation of forest cover change by subtraction of the km^2 of forest area reported in 1999 and 2001. Therefore a fraction of statewise forest burned in 1995 (FSI, http://www.fsiorg.net/Special%20Studies/Fire%20Mapping%20Country.html) was operated on the mean district-wise forest cover for 1999–2001, to obtain forest area burned.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gb/2005gb002547.

Table 1. Regionwise Forest Area and Area Burned of Open, Dense, and Very Dense Forest in Selected Regions

	Open and Dense Forest (IGBP 6–10)					
	Open Forest		Dense Forest		Very Dense (IGBP 1–5)	
Regions/States[a]	Forest Area, km^2	Area Burned, km^2	Forest Area, km^2	Area Burned, km^2	Forest Area, km^2	Area Burned, km^2
East-northeast	95,404 (68,538–132,804)	1264 (880–1836)	67,142 (48,234–93,462)	1364 (970–1922)	72,153 (51,834–100,437)	101 (26–392)
Central India	84,393 (60,628–117,476)	1975 (1501–2627)	144,615 (103,890–201,304)	3147 (2399–4114)	1785 (1282–2485)	0
South India	27,555 (19,795–38,357)	99 (50–198)	39,230 (28,182–54,608)	146 (75–283)	11,772 (8457–16387)	30 (9–94)
Western Indo-Gangetic plain	31,094 22,338–43,283	573 (426–779)	44,217 (31,765–61,551)	453 (284–785)	6614 (4752–9207)	254 (164–394)
Rest of India	20,282 (14,570–2,8232)	269 (185–395)	7023 (5045–9776)	130 (92–182)	22,257 (15,989–30,982)	297 (126–550)
India	**258,730** **(185,869–360,152)**	**4180** **(304–5836)**	**302,227** **(217,117–420,700)**	**5240** **(382–7286)**	**114,582** **(82,314–159,498)**	**681** **(365–1430)**

[a] For the definition of the regions see auxiliary Figure S1.

[9] The forest area burned was 681 km^2 "very dense," 5240 km^2 "dense" and 4180 km^2 "open" forest (Table 1). The burned area of 681 km^2 in "very dense" forests from FSI corresponds well to that from GBA-2000 of 426 km^2 in IGBP forest categories 1–5 [*Tansey et al.*, 2004], and this range was used as the uncertainty in "very dense" forest burning. The FSI burned area of 9420 km^2 in "dense and open" forest burned is a small fraction of the GBA-2000 reported burned area in shrublands/savanna of 43,286 km^2 [*Tansey et al.*, 2004]. The UMD land cover data set [*Hansen et al.*, 2000], used in GBA-2000 places about 133,800 km^2 of land under IGBP forest categories and 2,164,300 km^2 in IGBP shrubland/woodland categories 6–10. Both the FSI classification and the MODIS data set differ from the UMD data set and assign a large fraction of India's land use to croplands (IGBP 12 and 14). Specifically, FSI assigns 562,744 km^2 to "open and dense forest" corresponding to IGBP woodland-shrubland 6–10, with the balance 2,611,725 km^2 in nonforest lands [*FSI*, 2001], similar to MODIS land cover of 837604 km^2 in IGBP 6–10 and 2,403,819 km^2 in IGBP 12, 14. Therefore we estimate that about three fourths of the GBA-2000 burned areas in woodland-shrublands in India (32,000 km^2) would lie in croplands, and the balance (11,000 km^2) would be in the shrubland-woodland category, in reasonable agreement with the FSI burned area of 9420 km^2 in the corresponding category of "open and dense forest." We calculate significant crop waste burning from inventory methods in following sections in this work, consistent with the larger GBA-2000 burned area detection, which was, however, reported in an alternate vegetation class. While early studies estimated about 10,000 km^2 of forest area burned for shifting cultivation in 1984–1985 [*Kaul*, 1993], recent reports account for regeneration of forest from rotation of plots used for shifting cultivation [*Ranjan and Upadhyay*, 1999; *Haripriya*, 2003] and estimate about 975–1800 km^2 of forest land, largely in "open and dense forest" cleared annually for shifting cultivation.

2.1.2. Aboveground Fuel Load and Combustion Efficiency

[10] India-specific information is available as tree-species-wise aboveground biomass density [*Haripriya*, 2000] and at a state level, combining biomass density and forest area in the three crown density classes of very dense (70–100%), dense (40–70%) and open (10–40%) forests [*Chhabra et al.*, 2002] (Table 2). Ranges for available fuel load in Table 2 for the "very dense" forest category include those for temperate and tropical forests (60–100% crown cover) [*Hoelzemann et al.*, 2004; *Ito and Penner*, 2004], needleleaf and mixed coniferous trees [*Haripriya*, 2000], or

Table 2. Aboveground Fuel Load and Combustion Efficiency for Forest Biomass

	Aboveground Fuel Load, kg m^{-2}			Combustion Efficiency, %		
	Open and Dense (IGBP 6–10)			Open and Dense (IGBP 6–10)		
References	Open	Dense	Very Dense (IGBP 1–5)	Open	Dense	Very Dense (IGBP 1–5)
Crown density[a]	10–40%	40–70%	70–100%			
Hoelzemann et al. [2004][b]	1.80–4.80	4.48–5.92	14.60–27.00	0.6 ± 0.1	...	0.5 ± 0.1
Ito and Penner [2004][b]	1.39–2.53	8.95	16.07–16.09	0.37–0.61	...	0.33 ± 0.1
Chhabra et al. [2002][c]	2.10–5.60	6.50–12.20	13.70–20.00	...	...	...
Haripriya, [2000][c]	1.40–5.30	6.30–13.80	14.10–20.90	...	...	...
Present study[c]	**2.79**[d] **(1.39–5.60)**	**9.01** **(4.48–13.80)**	**16.64** **(13.50–20.50)**	0.48 **(0.37–0.61)**	**0.50** **(0.42–0.59)**	**0.41** **(0.33–0.5)**

[a] Crown density from *Chhabra et al.* [2002] reported for Indian forest.
[b] Values reported for South Asia.
[c] Values reported for India.
[d] Geometric mean calculated from the range reported in literature.

dense forests in the seven states identified in the previous section [*Chhabra et al.*, 2002]. “Dense” forests correspond roughly to woodlands or woody savanna (30–60%) in the global studies, in which estimated fuel loads are 1.39–2.53 (kg m^{-2}), where smoldering fires burn insignificant coarse wood or a high of 8.95 kg m^{-2},where slash-and-burn practices partially burn coarse wood. India-specific studies show teak, chirpine, deciduous and semi-evergreen trees in “dense forests” [*Haripriya*, 2000; *Chhabra et al.*, 2002] which occur in central and south India. Available fuel loads were estimated from these biomass densities using the relative distribution of biomass in stem, foliage and litter categories for different forest types [*Haripriya*, 2003]. Percentages of litter, leaf and coarse wood available for burning were assumed as 100%, 50% and 40%, the last value accounting for forest clearing for cultivation. This leads to a mean available fuel load of 6.3–13.8 kgm^{-2} in “dense” forests. “Open” forests correspond spatially to the shrubland and savanna categories IGBP 6–10, but not to grasslands, and correspond in available fuel load to the woody savanna with negligible burning of coarse wood. They contain species like bamboo, khair, salai, and occur in central and western India [*Haripriya*, 2000; *Chhabra et al.*, 2002], for which we estimate 1.8–5.5 kgm^{-2} available fuel load. Comparisons of the actual burning efficiency that results in each vegetation type are not presently available from India-specific studies, and introduces an uncertainty in the burning calculation, which is reflected in the ranges of fuel load used. Ranges of aboveground fuel load from the different data sources were used to estimate the geometric mean and standard deviation, shown in the last line of Table 2, for use in this work. Combustion efficiency (Table 2) is based on the relative amounts of litter, leaf, wood and fine roots and taken from reported ranges for the different forest categories [*Ito and Penner*, 2004; *Streets et al.*, 2003a].

2.2. Crop Waste

[11] Agricultural or crop waste, in the form of cereal straws, woody stalks, and sugarcane leaves/tops are generated during harvest periods, and find use as animal fodder, thatching for rural homes, residential cooking fuel and industrial fuel. Some fraction of the unutilized waste is burned in the field, and has a strong regional and crop-specific variation. The amount of unutilized crop waste was estimated in five categories of waste from cereals, pulses, oilseeds, fiber crops and sugarcane, as a balance between generation and known uses (please see auxiliary material Figure S2). Reported crop practices were used to assess the fraction of unutilized waste actually burned in field [*Karve et al.*, 2001; *Ministry of Environment and Forests*, 2004; B. Misri, personal communication, 2003]. Further assessment of the likelihood of field burning of wastes from different crop types is made in section 4.1.

2.2.1. Crop Waste Generation and Utilization

[12] Statewise crop waste generated was estimated from crop production data [*FAI*, 2001] for thirteen different crop types for India, and aggregated into the 5 categories above. Waste to grain ratio (or residue-to-product ratio, RPR) reported in literature [*Koopmans and Koppejan*, 1997; *Smill*, 1999] and in India-specific studies [*Singh and Rangnekar*, 1986; *Bhattacharya et al.*, 1993; *Painuly et al.*, 1995] (see auxiliary material Table S1), with uncertainty range of 12–62% (95% confidence interval), was used to calculate the waste generated. Dry matter fraction and combustion efficiency, specific to crop-waste types, were assumed from earlier studies [*Koopmans and Koppejan*, 1997; *Smill*, 1999; *Streets et al.*, 2003a]. The fraction of waste plowed into the field after harvest, to add to the fertilizer content of the soil, has not been reported for Indian cropping practices and is not accounted for in this work, but is believed to not introduce significant uncertainty. Estimated crop waste generated (see Figure S3a in auxiliary material) was largely from cereal straws, with the balance divided equally among the other four categories. Waste generation was higher in north and western India, from the larger crop production in these regions.

[13] The consumption of crop waste as animal fodder was estimated from animal population reported by *Ministry of Agriculture* [1999] and per capita daily dry feed requirements [*Amble et al.*, 1965] of various animal categories (see Table S2 in auxiliary material). The percentage of crop waste in animal feed (Food and Agriculture Organization, FAOSTAT database collection, 1999, http://faostat.fao.org/) [also *Safley et al.*, 1992] was based on the estimated roughage in the diet, and ranged from 74 to 85% for dairy and nondairy cattle, 50 to 60% for pigs and a minor 0 to 5% for sheep and goats. These data were found to be consistent with other regional studies on animal feed requirements [*Ramachandra et al.*, 2000; *Devendra and Sevilla*, 2002]. The statewise cattle and livestock population for 2000–2001 in the four major categories was obtained by extrapolating from the 1992 cattle census, using the national growth rate of cattle during 1987–1992 [*Ministry of Agriculture*, 1999], the latest report available at the time of this work. Animal fodder is primarily from cereal straws (85%), with the balance from pulses and oilseeds [*Ravindranath and Hall*, 1995]. Crop-waste use for cooking was taken from a previous study that estimated biofuel combustion from cooking from food consumption and fuel use data [*Habib et al.*, 2004] and ranged from 36 to 67 Tg yr^{-1}, with a 95% confidence interval uncertainty of 86% (at 95% confidence interval). This was distributed among categories of waste from oilseeds (40%), fiber crops (30%), pulses (25%) and cereal straws (5%) [*Ravindranath and Hall*, 1995]. A minor use of crop waste use as thatching material (2% of generated rice straw) [*Ravindranath and Hall*, 1995] was applied statewise.

[14] Crop waste used for fodder (see auxiliary Figure S3b) was seen to be high in states with high crop waste generation patterns, consistent with the prevailing practice of animal rearing in predominantly agricultural areas. Crop waste is transported only over short distances because of its low bulk density and high transportation costs [*Kumar et al.*, 2002]. The similarity in crop waste generation and fodder use, derived from different sources of data relating to agriculture and animal husbandry, respectively, is therefore consistent with the predominantly local use of crop waste.

2.2.2. Unutilized Crop Waste

[15] Unutilized crop waste was estimated from a balance between generation and known uses, aggregating data for

13 crop types in five categories of cereal straws, waste from pulses, oilseeds, fiber crops and sugarcane and "other." In states with an individually low crop waste generation, accounting in sum for 6% of the national generation, the crop waste use exceeded generation by a minor amount. This was resolved by reducing the uses to zero, in decreasing order of the uncertainty with which they were known, i.e., first thatching and then fodder. Biofuel use was not altered as it was derived from a broad data set of food consumption statistics and fuel mix [*Habib et al.*, 2004], and had lower estimation error of 86% compared to the other uses. In all cases, the changes made lay within the uncertainty bounds of crop waste generated and the estimated unutilized waste. Unutilized crop waste was largely in the form of cereal straws, followed by woody stalks from fiber crop, oilseed and pulses and tops and leaves from sugarcane (please see auxiliary Figure S4). Waste availability was high in the western Indo-Gangetic plain, followed by central and south India, with negligible amounts remaining unutilized in east-northeast India. The use of fodder and biofuel consumption to make an explicit calculation of unutilized crop waste would reduce uncertainty in comparison to previous methods which assume a fraction of generated crop waste to be burned in field.

2.3. Seasonal and Regional Distribution in MODIS Active Fires in Forests, Shrublands, and Croplands

[16] High-resolution satellite data of active fires [*Justice et al.*, 2002] and land cover classification [*Friedl et al.*, 2002] from MODIS, both on a scale of 1 km × 1 km, have been analyzed to derive the seasonal and spatial variability in fire frequency between 2001 and 2003. The early MODIS fire product was adversely affected by hardware problems, which were resolved in about November 2000, leading to significantly improved quality of fire detection [*Justice et al.*, 2002]. A number of fires were also missed from a conservative nature of the MODIS cloud mask, but a procedure to eradicate this problem was implemented in early 2001. The data used here are from 2001–2003, after eradication of the early problems. Preliminary validation of MODIS active fires over southern Africa showed appropriate behavior in relation to data from coincident pixels from the ASTER instrument, also aboard the TERRA platform [*Justice et al.*, 2002].

[17] The MODIS land cover product supplies an IGBP land cover classification from which we consider categories of "very dense" forest (IGBP 1–5) and "dense and open" forest (IGBP 6–10). In these land cover classes, the collocated fires detected by the two overpasses (night and day) of the MODIS were counted. We retain only fires with a nominal or high level of confidence. We have also considered the possible underestimation of the total number of fires per month due to cloud cover or no observations by the satellite. The probability P_f to have a fire in case of cloud or no data is approximated by the frequency of occurrence of nominal and high level of confidence fires on a monthly basis for a given land cover class for each 25 km × 25 km box. The total number of fires is then the sum of nominal and high level of confidence fires and the product of P_f by the total of number of missing or cloudy pixels.

$$\begin{aligned} P_f = {} & N(\text{nominal and high confidence}) \\ & /[N(\text{nominal and high confidence}) \\ & + N(\text{no fire} + \text{low confidence} + \text{unknown})] \end{aligned} \tag{1}$$

$$\begin{aligned} N_{total} = {} & N(\text{nominal} + \text{high confidence}) \\ & + P_f {*} N(\text{cloud} + \text{missing pixels}). \end{aligned} \tag{2}$$

[18] It is likely that the probability P_f in a clear sky differs from that in a cloudy sky and perhaps between cloud with rain and cloud without rain. The statistics in applying the P_f correction were analyzed by calculating the number of fires with and without the P_f correction in four land cover classes forests (IGBP 1–5), woodland/shrublands (IGBP 5–10) and croplands (IGBP 12, 14) in the four selected regions of India (please see auxiliary material Figure S1). The monthly mean change was small and varied between 1 and 4% in all months in a given land cover class.

[19] Monthly mean MODIS fires in four selected regions (please see auxiliary Figures S5a–S5d), believed to have similar forest burning and agricultural practices, show that the fire season repeats each year during February to June. The peak in forest burning in east-northeast and central India is in March (please see auxiliary Figures S5a and S5b), but is in April–May in the western Indo-Gangetic plain (auxiliary Figure S5d), from a delay in onset of burning. The fire season matches with that from a previous analysis using ATSR-2 fire counts over India, however without land cover mapping and with the assumption that all detected fires were from forest burning [*Reddy et al.*, 2002; *Reddy and Boucher*, 2004]. The fires detected in central India during October–January are from shrubland burning during the dry season in the western part of central India. There is a large fire frequency in the east-northeast, which occurs in "very dense" forests, followed by significant fires in central India, in "dense and open" forests, and negligible fire frequency in the south and western Indo-Gangetic plain from forest burning (note different scales in different regions in auxiliary Figure S5d). There is larger interannual variability in forest burning in the northeast, specifically in "very dense" forests (auxiliary Figure S5a), not seen in central India. The MODIS fire frequencies were used to spatially and temporally distribute the forest biomass burning.

[20] Active fires in croplands (IGBP categories 12 and 14) were also analyzed for seasonal and regional variability (auxiliary Figures S5a–S5d) and used to identify types of crop waste subject to field burning and distribute the inventory estimate seasonally and spatially. Interestingly, it was seen that majority of the cropland fires occur in the western Indo-Gangetic plain, with a smaller amount in central India and negligible burning in the east-northeast and south. This corroborates India's national communication to the UNFCCC [*Ministry of Environment and Forests*, 2004], which also estimated crop waste burning largely in states within this region. The seasonal cycle in cropland fires is distinct on the basis of region. In the western Indo-

Table 3. Emission Factors of Aerosols and Trace Gases for Forest and Crop Waste Open Burning

	Emission Factors,[a] gkg^{-1}					
	Forest Burning		Crop Waste Burning			
Pollutants	Open/Dense (IGBP 6–10)[b,c]	Very Dense (IGBP 1–5)[c]	Cereals[d]	Sugarcane[d]	Others[e]	All Types
		Aerosols				
BC	0.5–0.6	0.6–0.9	0.8–1.5	0.6–0.7	0.7–1.0	
OC	5.6–9.1	9.1–9.7	2.0–4.1	1.5–1.7	1.7–2.7	
OM	6.6–10.3[f]	10.3–14.2[f]	4.4–6.8[g]	3.1–3.6[g]	3.7–5.0	
$PM_{2.5}$	8.4–13.0	13.0–26.7	5.5–10.1	3.9–4.1	4.6–6.4	
		Trace Gases				
CO_2	1591–1613	1569–1826				1515–1862
CO	83–107	107–180				92–257
SO_2	0.6–1.0	1.0–1.5				0.4–0.6
NO_x	3.4–3.9	3.0–5.7				2.5–4.5
CH_4	3.3–4.7	4.7–8.4				2.7–4
NMVOC	7.4–9.7	5.7–14.7				15.7–23.4
NH_3	1.2–1.4	1.4–3.0				1.3–1.9

[a] The emission factors are the central value and upper bound calculated at 95% CI.

[b] From *Andreae and Merlet* [2001], calculated as geometric mean of emission factors reported for savanna/grassland and extratropical forest.

[c] From *Andreae and Merlet* [2001] for extratropical forest.

[d] From *Turn et al.* [1997].

[e] From *Turn et al.* [1997], calculated as geometric mean of emission factors reported for cereals and sugarcane.

[f] Average OM/$PM_{2.5}$ ratio (0.8) for tropical forest, derived from *Yamasoe et al.* [2000] and *Ferek et al.* [1998] and applied to $PM_{2.5}$ emission factors to calculate OM emission factors.

[g] Average OM factors for cereals and sugarcane, derived from *Turn et al.* [1997].

Gangetic plain (auxiliary figure S5d) the cycle with peaks in May and October corresponding to the two major harvest seasons, respectively, of Kharif and Rabi. Peaks in fire frequency are not so narrow in central India where cropland fires occur during January–April and October–December. In south and east-northeast India, they occur in February–March, consistent with a major harvest season in south India in January–February. Interannual variability in cropland fires is lower than in forest fires, indicating their anthropogenic origin and specific purpose of field clearing following harvest. Seasonal distributions of fire counts in forests and croplands are used to distribute forest-burning emissions as described in section 4.3.

3. Emission Factors of Pollutants From Biomass Burning: Forests, Shrublands, and Crop Waste

[21] We consider emissions of aerosols including particle matter smaller than 2.5 μm diameter ($PM_{2.5}$) and its constituents black carbon (BC), organic matter (OM) which includes organic carbon and associated hydrogen/oxygen and other compounds, inorganic oxidized matter (IOM) calculated as the balance between PM2.5 and BC plus OM and gaseous pollutants including CO_2, CO and others as shown in Table 3. Reported source specific aerosol composition was used to estimate OM, rather than report OC, which would need a conversion factor to OM, prior to use in atmospheric models. Previous estimates of forest burning from India [*Streets et al.*, 2003a; *Bond et al.*, 2004] used emission factors from *Andreae and Merlet* [2001] for the extratropical forest category. Here, on the basis of the ranges of expected aboveground fuel load, we used the extratropical forest emission factors for the "very dense" forest category and a geometric mean emission factor from extratropical forest and savanna/grassland for "open and dense" forests (Table 3). The OM emission factors were derived from chemical compositions of forest burning aerosol reported on by *Ferek et al.* [1998] and *Yamasoe et al.* [2000] using a mass balance approach to calculate organic matter (OM) as the difference between gravimetrically measured PM and chemically measured EC, ions and trace metals.

[22] Aerosol emission factors for crop waste burning were taken from *Turn et al.* [1997], who reported measurements for individual crop wastes like cereal straws (i.e., rice, wheat, barley) and sugarcane. The significantly large ion and crustal element content reported in this work differs from previously reported chemical composition of particulate emissions from grassland burning and sugarcane waste burning [*Andreae and Merlet*, 2001] and seem anomalous (45–50%). Use of these large crustal element contents as IOM resulted in a low OM/OC ratio, estimated as [PM2.5 − (BC + IOM + OC)]/OC, of between 0.8 and 1.1, not reported elsewhere for open burning. To make the OM/OC ratio consistent with other reported open burning studies, we use PM2.5, BC and OC emission factors for various crop wastes from *Turn et al.* [1997] with the OM/PM2.5 ratio derived from a mass balance approach using chemical composition for savanna/grassland fires from *Ferek et al.* [1998] and *Yamasoe et al.* [2000]. A single emission factor for all crop waste types was used in previous work [*Streets et al.*, 2003a; *Bond et al.*, 2004]. Emission factors for CO_2 and trace gases used were the same as used for crop waste burning in previous work [*Streets et al.*, 2003a; *Andreae and Merlet*, 2001].

4. Results and Discussion

4.1. Evaluation of Regional and Seasonal Variability in Bottom-Up and Top-Down Methods

[23] Monthly mean values in bottom-up estimates of forest and crop waste burning were evaluated with MODIS

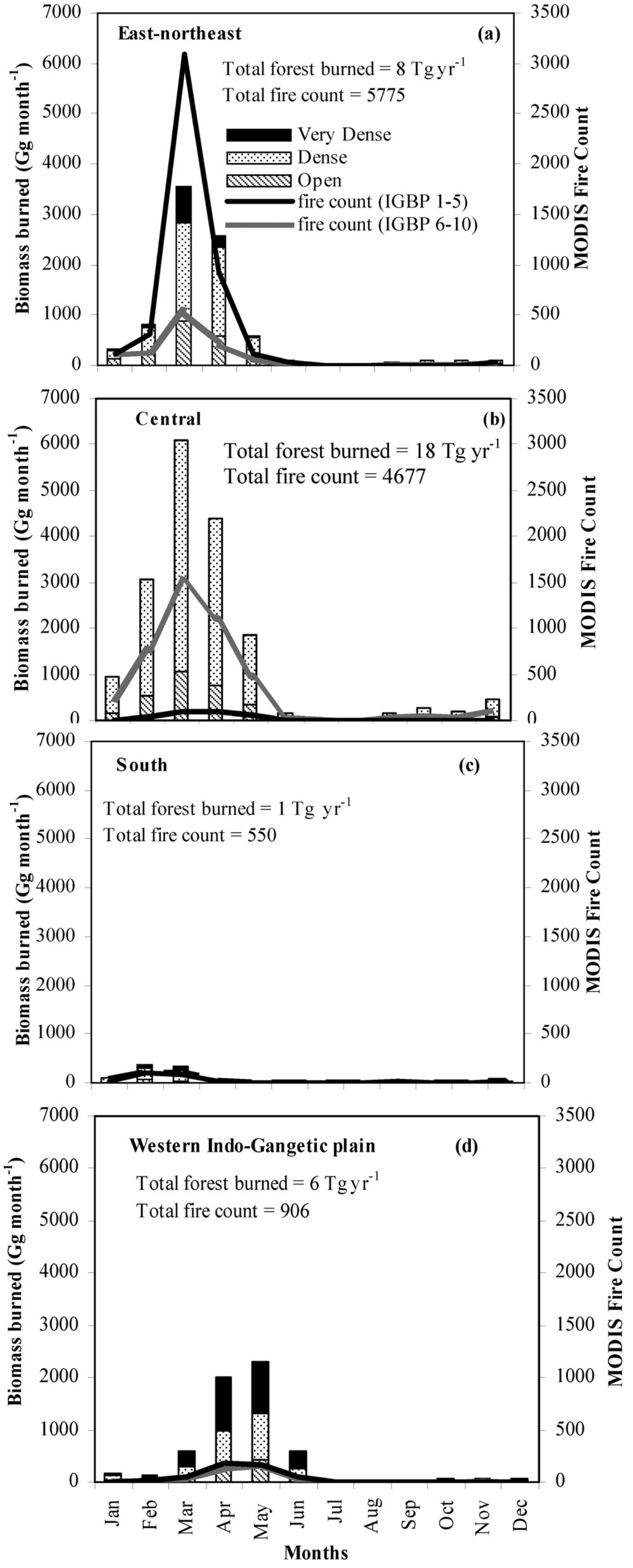

Figure 1. Monthly mean forest biomass burning and MODIS fire counts averaged from 2001–2003 in selected regions.

fires in the respective land types in the four regions selected. In this analysis we preserve the spatial distribution of both methods and examine consistency between them. The annual mean spatial distribution in forest biomass burned (Figures 1a–1d) was based on the inventory estimate of district level forest burning (section 2.1), gridded on a 25 km × 25 km resolution and aggregated in the selected regions (please see auxiliary Figure S1), but without a seasonal cycle. A similar aggregation was made of MODIS fires over the 3 years. Regional differences in amounts of forest biomass burned differ from corresponding forest fire counts with biomass burned being largest in central India but fire frequency being highest in the east-northeast. Such a difference is also found among forest categories from discrepancy between the detected fire frequency and the reported area burned, used in the bottom-up forest-burning estimate. For example, in "very dense" (IGBP 1–5) forests, in the east-northeast (Figure 1a) and south (Figure 1c), there is a large fire frequency but a very small area of forest burned (Table 1). In the western Indo-Gangetic plain (Figure 1d), there is better agreement, with about 50% of fire detection and burned area in "very dense" forests. In central India a low 6% of the fire counts are in "very dense" forests, consistent with no estimated biomass burning in the inventory calculation. These differences arise from the assumptions of the mean statewise area burned and mean biomass densities in each forest type. Comparison of the present spatial and temporal distributions of biomass burned with biomass density gradients on a finer spatial scale would be needed to capture these differences more accurately. In this work, the MODIS fire frequencies were used to spatially and temporally distribute the forest biomass burning.

[24] Seasonality of crop waste open burning in the inventory estimate was derived from reported harvest months for 13 crop types in each state of India [*FAI*, 2001]. It was first assumed that crop waste burning occurred throughout the harvest season; for example, in Uttar Pradesh, the largest rice producing state, burning of waste from cereals was distributed between March and June, while sugarcane was distributed from October to December, corresponding to the reported harvesting months. A seasonal aggregation of the amounts burned in the four regions showed a mismatch with the MODIS fire cycle. A change in the assumption that field burning of crop waste started one month after the start of the harvesting season and continued until the end of the season, resulted in the best match, with the MODIS cropland fire cycle, for cereals and sugarcane (Figures 2a–2d). Cereal straws and sugarcane waste (leaves/tops) are entirely burned in fields [*Karve et al.*, 2001]. Sugarcane tops and leaves are in fact burned as an integral part of the harvest procedure to gain access to the cane. On the basis of this agreement between satellite fire seasonality and reported field practice, unutilized sugarcane and cereals waste was assumed completely burned in field. The inventory estimate placed crop waste burning in the western Indo-Gangetic plain in November and December, but there was negligible MODIS fire detection in these months. In such cases, the seasonality from the satellite sensor was imposed upon the annual inventory estimate.

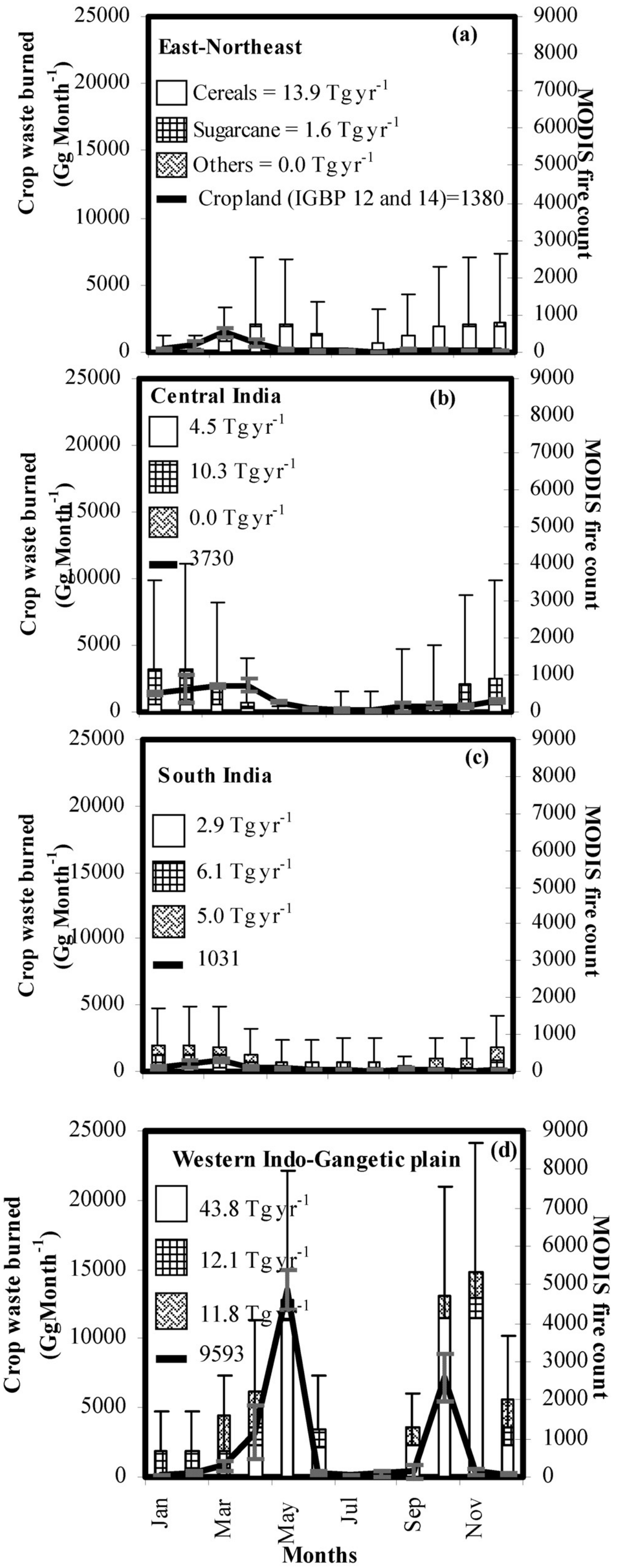

Figure 2. Monthly mean crop waste burning and MODIS fire counts in selected regions.

[25] The seasonality in availability of unutilized waste available from the harvest of pulses in February–March and oilseeds in September–November and fiber crops in January–March and October–December, did not match that in MODIS cropland fires. Burning patterns from field experience, indicate that wastes from fiber crops, pulses and oilseeds find use as industrial fuels [*Kumar et al.*, 2002] or may be stored for future use as biofuels (Misri, personal communication, 2003) in several parts of India. However, it is reported that all crop waste is burned in the Indo-Gangetic plain, in Haryana, Uttaranchal, western Uttar Pradesh, and Punjab, and in the south in Karnataka, from the introduction of mechanized harvesting in these states [*Ministry of Environment and Forests*, 2004]. On this basis, it was decided to exclude waste from pulses, oilseeds and fiber crops from crop waste burning estimate, except in the states listed above. This assumption differs from previous works [*Streets et al.*, 2003a; *Reddy et al.*, 2002] where a fixed fraction of generated crop waste of all types was assumed burned in the field. The additional information available from satellite fire counts and field experience allows us to make a more realistic assumption based on types of crop waste actually subjected to burning in different regions of India. The number of MODIS cropland fires and mass of unutilized crop waste from the inventory estimate were both large in the western Indo-Gangetic plain. However, the amounts of unutilized crop waste in the four regions were not strictly proportional to the active-fire counts (Figures 2a–2d).

[26] MODIS active-fire maps are therefore useful to capture the seasonal variability of forest and crop waste burning. Correspondence in satellite detected fire cycles with harvest season was used to identify types of crop waste burned in different regions. The geographical distribution of active fires, however, may not accurately represent that in the actual amounts of biomass burned, and must be used with caution to redistribute biomass burned at least on spatial scales considered in this study. This is consistent with previous studies which have cautioned against using active-fire counts to estimate biomass burned [*Hoelzemann et al.*, 2004; *Simon et al.*, 2004] and reported a discrepancy between active-fire and burned-area detection by satellites, indicating that incidence of fire and the area or amount of biomass burned do not correlate well. Specifically, the GBA-2000 burned area product detected significantly lower burning activity in India than that indicated by the active-fire products, for example, the ATSR-2 World Fire Atlas and the Global Fire Product [*Tansey et al.*, 2004], implying that the fire products probably detect several short-lived, small fires, which do not result in significant area burned. Comparison with India data from a global biomass burning inventory using the areal extent of the fire and estimated biomass fuel loads [*van der Werf et al.*, 2003] is being undertaken as a follow-up study. Confounding fires of other origin, for example, coal mines, and oil/gas fields have not be looked at specifically, but may not cause a significant problem, because of identical 1 km × 1 km resolution of land classification and active-fire pixels from MODIS.

Table 4. National Estimates of Biomass Burned and Emission of Aerosols and Trace Gases for Forest and Crop Waste Open Burning

	Emissions[a]								
	Forest Burning				Crop Waste Burning (IGBP 12 and 14)				
Biomass Burned/Pollutants	Open (IGBP 6–10)	Dense (IGBP 6–10)	Very Dense (IGBP 1–5)	Total Forest	Cereals	Sugarcane	Others	Total Crop Waste	Total Open Burning
Biomass burned, $\mathrm{Tg\ yr^{-1}}$	6–12	21–39	5–10	32–61	67–189	32–70	17–30	116–289	148–350
Pollutants									
				Aerosols					
BC	3–7	11–22	3–9	16–38	55–292	19–49	12–31	86–372	102–409
OC	31–108	115–354	42–97	188–559	134–770	48–122	29–79	211–970	399–1529
OM	36–122	135–400	47–141	219–663	287–1250	97–247	60–143	444–1639	663–2303
$\mathrm{PM_{2.5}}$	46–154	173–504	60–266	279–924	369–1913	125–289	78–191	572–2393	851–3317
				Trace Gases					
$\mathrm{CO_2}$, $\mathrm{Tg\ yr^{-1}}$	9–19	33–63	7–18	49–100	102–353	48–131	25–55	175–539	224–638
CO, $\mathrm{Tg\ yr^{-1}}$	0.5–1.3	1.7–4.2	0.5–1.8	3–7	6–49	3–18	2–8	10–74	13–81
$\mathrm{SO_2}$	3–12	12–39	5–15	20–65	27–113	13–42	7–18	46–172	66–238
$\mathrm{NO_x}$	19–46	70–151	14–57	103–255	168–845	80–313	42–132	289–1290	393–1545
$\mathrm{CH_4}$	18–56	68–182	22–84	108–322	181–762	86–283	45–119	313–1164	420–1486
NMVOC	41–115	153–377	26–147	221–639	1055–4430	500–1644	263–693	1818–6767	2039–7406
$\mathrm{NH_3}$	7–17	25–54	6–30	38–100	87–367	41–136	22–57	151–560	189–661

[a] Emissions are the central value and upper bound at 95% CI. Unites are $\mathrm{Gg\ yr^{-1}}$ unless otherwise specified.

4.2. Forest, Shrubland, and Crop Waste Burned

[27] Forest and shrubland biomass burned in India was estimated as 32 (16–61) $\mathrm{Tg\ yr^{-1}}$ (please see auxiliary Figure S6). Most of this burning, of 27 (14–51) $\mathrm{Tg\ yr^{-1}}$ occurs in "open and dense" forest with low-density biomass cover (corresponding to IGBP categories 6–10), with 5 (2–10) $\mathrm{Tg\ yr^{-1}}$ in "very dense" forests (IGBP categories 1–5). The central value does not differ significantly from the previous estimates for India [*Streets et al.*, 2003a], which was made from climatological mean estimates of *Hao and Liu* [1994]. However, the estimate in the present work is reconciled with India-specific inventory studies and global burned-area studies [*Reddy and Venkataraman*, 2002a; *Streets et al.*, 2003a; *Hoelzemann et al.*, 2004; *Tansey et al.*, 2004] and has a well-bounded uncertainty of 97% (95% confidence interval) on forest and shrubland biomass burned.

[28] From the analysis in section 4.1 we retain the assumption that unutilized cereal and sugarcane waste, are burned in field throughout India, while that from oilseeds, fiber crops and pulses are burnt only in states which have mechanized harvesting. This leads to crop waste burning of 116 (58–289) $\mathrm{Tg\ yr^{-1}}$ (please see auxiliary Figure S7). The central values and upper bounds of the fraction of waste burned in field were 17–35% for cereal waste and 9–10% for other crop waste. For sugarcane, about 50% of the generated waste is burned, considering the dry matter fraction and combustion efficiency. Fraction burned was 18–30% on an all-India basis, higher in the western Indo-Gangetic plain (30–40%), but much lower in other parts of India (12–18%). Recent assumptions of 20–25% fraction burned [*Yevich and Logan*, 2003; *Streets et al.*, 2003a; *Bond et al.*, 2004], and the amounts of crop waste burned are in the range estimated here.

4.3. Emissions of BC, OM, and Gaseous Pollutants

[29] We report the central and upper bound (95% confidence interval) values of the emissions from open burning of BC, OM, $\mathrm{PM_{2.5}}$, $\mathrm{CO_2}$, CO and other trace gases (Table 4) and the relative contributions to these pollutants from various combustion sources in the inventory, including fossil fuel and residential biofuel combustion [*Reddy and Venkataraman*, 2002b; *Streets et al.*, 2003b; *Bond et al.*, 2004; *Venkataraman et al.*, 2005] (Figure 3). As explained in the emission factors section, OM from biofuel and biomass burning is estimated using a mass balance approach, as the difference between gravimetrically measured PM and chemically measured EC, ions and trace metals. This is based on the low mineral content of biomass, compared to fossil fuels like coal, whose combustion results in emissions of mineral matter as fly ash [*Reddy and Venkataraman*, 2002b]. The estimated OM for biofuels and biomass burning could include insoluble mineral constituents, associated with trace elements, which however contribute only 1% of the particle mass.

[30] Open burning contributes importantly (about 25%) to BC, OC/OM and CO emissions, a smaller amount (9–13%) to $\mathrm{PM_{2.5}}$ and $\mathrm{CO_2}$ emissions, and negligibly to $\mathrm{SO_2}$ emissions (1%). However, it cannot explain a large "missing source" of BC from India [*Dickerson et al.*, 2002] or CO from Asia [*Kasibhatla et al.*, 2002], suggested in previous studies. The larger contribution of fossil fuels to $\mathrm{PM_{2.5}}$ than to OM comes from the large inorganic mineral matter emissions, shown as IOM (first bar, Figure 3) from this source, which is essentially absent in emissions from biofuels and biomass burning.

[31] Spatial and seasonal distributions of BC, OM, $\mathrm{PM_{2.5}}$ and CO emissions from forest burning were derived by imposing the monthly mean MODIS derived active-fire cycle on the annual mean spatial distributions derived from

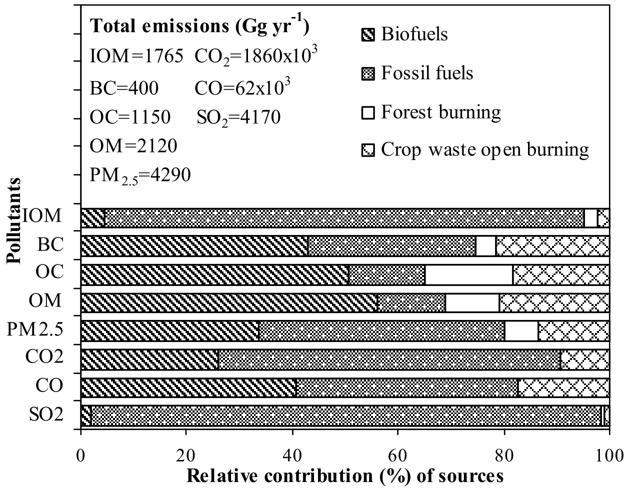

Figure 3. Source contributions to pollutant emissions from India.

the inventory approach for both forest and cropland burning, at a 25 km × 25 km resolution. Since identical high-resolution data from MODIS were used for the active-fires and land cover classification, this involved aggregation of the 1 km × 1 km product into 25 km × 25 km grids, as the land cover type within each grid was explicitly known.

[32] Emissions from forest burning aggregated over the fire season of January–May were dominant in central India (mainly Chattisgarh) and coastal Orissa (auxiliary Figure S8), followed by the western Indo-Gangetic plain. Crop waste open burning, showed a different spatial pattern in January–June and September–December (auxiliary Figure S9a and S9b). During January–June, the highest emissions occur in western Indo-Gangetic plain, west and southern regions while during September–December emissions are mostly in the western Indo-Gangetic plain (auxiliary Figure S9b). Largest overall emissions from open burning are in March–May and October with the peak in March from forest burning and in May and October from crop waste burning (Figure 4). The harvesting of cereal wastes and their field burning in major agricultural states like Punjab, Haryana and western Uttar Pradesh is the largest potential contributor of these emissions.

4.4. Uncertainties

[33] A specific goal of the methodology developed, for estimating forest and crop waste biomass burned in field and associated emissions, was that the uncertainties in all input variables were characterized and propagated to obtain upper and lower bounds (at 95% confidence interval). For multiplicative independent variables, used to calculate biomass burned and related emissions, the relative precision was propagated in quadrature to obtain the uncertainty. For national level estimates, the absolute precision in statewise variables was linearly added to obtain the uncertainty, as the individual state values were derived from common input data and therefore not independent. The 95% confidence intervals for biomass burned were calculated as 1.96 times the absolute precision. The lower/upper bounds were derived assuming lognormally distributed uncertainties, following *Bond et al.* [2004].

[34] The uncertainty on forest biomass burned and crop waste burned are 97% and 150% respectively. Propagating these along with best literature emission factor ranges result in uncertainties on BC and OC of about 300%, down from 550–700% reported in previous studies [*Streets et al.*, 2003a]. Further reduction of these uncertainties would require measurements of region-specific emission factors from open burning. These reductions were largely from reduced uncertainty in biomass burning estimates in this work. With these new estimates the uncertainties on aerosol emissions from Indian region are well characterized and comparable with other regions of Asia including Japan and China [*Streets et al.*, 2003a]. The uncertainty on CO_2 emissions also reduced to 180% from 300% in previous studies [*Streets et al.*, 2003a]. The uncertainties on SO_2, NO_x, CH_4, NMVOC, NH_3 are about 250–300%.

5. Conclusions

[35] We estimated the forest burning from burned area and biomass density specific for Indian ecosystems and crop waste burning as a balance between generation and known uses as residential and industrial fuel and fodder, for the base year 2001. Crop waste burning was estimated as of 116 (58–289) Tg yr^{-1} as the central value and 95% CI uncertainty range, resulting in fraction burned ranged 18–30% on an all-India basis, but with strong regional variation. Forest and shrubland biomass burned in India was estimated as 32 (16–61) Tg yr^{-1}, with the largest burning in central India followed by the east-northeast.

[36] MODIS active-fire maps are useful to capture the seasonal variability of forest and crop waste burning. Correspondence in satellite detected fire cycles with harvest season, was used to identify types crop waste burned in different regions. The peak in forest biomass burning occurs in February–May, and crop waste burning varied with geographical location, with peaks in April and October, corresponding to the two major harvest seasons. The geo-

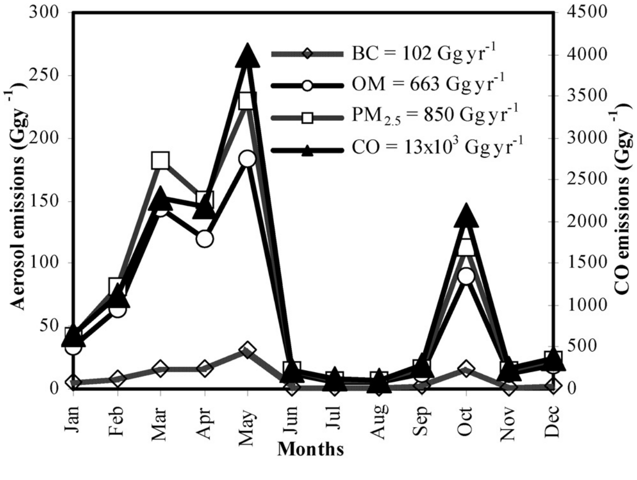

Figure 4. Seasonal emissions of pollutants BC, OM, $PM_{2.5}$, and CO emissions from open biomass burning.

graphical distribution of active fires, however, may not accurately represent that in the actual amounts of biomass burned, and must be used with caution to redistribute biomass burned at least on spatial scales considered in this study. Geographical variability in amount of forest biomass and crop waste burned differed from corresponding fire counts in forest and croplands, respectively; the amounts of biomass burned in four selected regions were not strictly proportional to the fire counts.

[37] We report emissions from open biomass burning of BC, OM, $PM_{2.5}$, CO_2, CO and SO_2 and the relative contributions to these pollutants from various combustion sources, including fossil fuel and residential biofuel. Open biomass burning contributes importantly (about 25%) to BC, OC/OM and CO emissions, a smaller amount (9–13%) to $PM_{2.5}$ and CO_2 emissions, and negligibly to SO_2 emissions (1%). However, it cannot explain a large "missing source" of BC or CO from India. The uncertainty on BC and OC emissions have been reduced to about 300% from 550–700% reported in previous studies, largely from reduced uncertainty in biomass burning estimates in this work.

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