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ORIGINAL ARTICLE

Assessment of trace gases, carbon and nitrogen emissions from field burning of agricultural residues in India

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Abstract Field burning of crop residue (FBCR) is becoming a growing environmental concern in developing countries. In this instance, a comprehensive crop-wise and spatially distributed study on the FBCR emissions from India for the period 1980 through 2010 have been undertaken, that covers: residue generation, its types, use pattern, and estimates of carbon, nitrogen, CH_4, CO, N_2O and NO_X emissions; along with associated uncertainties. FBCR contributed about 44 and 14% of the non-biofuel biomass and total biomass burning, respectively in India in the year 2000. The total dry residue generated are estimated as 217, 239 and 253 Tg, of which 45, 60 and 63 Tg of dry biomass are estimated to be subjected to FBCR in the years 1994, 2005 and 2010, respectively. Wheat and rice crops together accounted for about 76% of this. Burning of such huge amount of biomass is estimated to emit 22.4, 24.4 and 26.1 Tg of carbon; 0.30, 0.33 and 0.35 Tg of nitrogen; 4.18, 4.59 and 4.86 Tg carbon dioxide equivalent of greenhouse gases (GHG, viz., CH_4 and N_2O; which is over 1% of the Indian agriculture sector GHG emissions); 2951, 3,240 and 3,431 Gg of CO; and 120.8, 132.9 and 140.6 Gg NO_x emissions in 1994, 2005 and 2010, respectively. Further, the Indian states of U.P, Punjab, Haryana, M.P, Maharashtra, T.N, Karnataka, Andhra Pradesh, Bihar and W.B have been found to contribute maximum to the Indian FBCR emissions. FBCR avoidance and optimum utilization of crop-residue resource is urgently required for agro-ecosystem sustainability in the region.

Keywords Crop-residue · GHG · Inventory · Biomass-burning · Carbon–nitrogen loss

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Introduction

The total biomass burnt globally has been estimated as 6,800 (Crutzen et al. 1979), 8680 (Levine 1990), and 8600 (Andreae and Merlet 2001) Tg/year, of which the share of the agriculture waste are estimated to be 1900, 2020 and 540 Tg/year, by the respective workers. Biomass burning, in general, continues to be associated with large information gaps and uncertainties especially for the developing world regions like the Indian sub-continent. Streets et al. (2003) have stressed the urgent need for biomass burning studies in the Indian region. Of the various types of biomass burning (Levine 1991), the common practice of field burning of crop residue (FBCR) is becoming significant in the developing countries, and an increasingly common environmental concern in the Indian-sub continent, that has scarcely been studied. The lack of feasible disposable options in general, poor degradability of some crop residues, low fodder value of some residues, short-time gap available between harvesting and sowing of some crops, use of combine harvesters, etc. are responsible for increasing FBCR which is a concerning emission source (Gupta et al. 2004a and Sahai et al. 2007) for the Indian region. In India FBCR contributed about 44 and 14% of the non-biofuel biomass and total biomass burning, respectively, whereas, it contributed about 8 and 4% to those of Asia, respectively in the year 2000. Further, Indian FBCR contributed about 23% to the Asian crop-residue burning in the year 2000.

FBCR emits trace gases (e.g. CO_2, CH_4, CO, N_2O, NO_X, hydrocarbons, etc.) and particulate matter leading to deleterious impacts on human health, natural environment and ecological system (Cheng et al. 2000). Of these CO_2, CH_4 and N_2O are greenhouse gases (GHGs; Levine 2003) and CO reacts chemically with OH radical in the atmosphere, thereby affecting the concentration of CH_4 (Houghton 1991). The significance of emissions of these species have been studied by Levine (1990), Andreae and Crutzen (1997), Cheng et al. (2000), Tsai and Chyan (2006), Hirota et al. (2007), Sahai et al. (2007) and others. Some estimates of Indian emissions from FBCR such as by Streets et al. (2003), Yevich and Logan (2003), Gupta et al. (2004b) and NATCOM (2004) are available, however a comprehensive study of the FBCR emissions for the Indian sub-continent is still not available. Efforts have thus been mounted to develop country specific emission inventory for various trace gas species, based on the IPCC methodology (IPCC 1996) and IPCC good practice guidance (IPCC 2000), for this source. The present study reports country-specific emission inventory of CH_4, CO, N_2O and NO_X from FBCR for India: crop-wise for the years 1980–2010; and state-wise for the years 1994, 2000 and 2005. Burning of crop residue is not considered to be a net source of carbon dioxide (CO_2) by IPCC methodology (IPCC 1995) because the carbon released to the atmosphere during burning is reabsorbed during the next growing season (Houghton 1991; Levine 2003). This study also addresses some of the knowledge gaps related to residue generation, its types, use pattern, hotspot identification of major source areas, estimates of carbon and nitrogen emitted besides quantification of uncertainties. Based on various parameters nine crops have been identified for their significant contribution to the FBCR emissions in India, that have been considered in the present study. Due to lack of certainty in the available estimates the present work also tries to quantify related uncertainties. The work was initiated as part of the India's national communication (NATCOM) activity [for communication to United Nation Framework Convention on Climate Change (UNFCCC)] for the preparation of national emission inventory for FBCR for the base year 1994, that was subsequently carried forward to cover the three decades from 1980 through 2010. The results obtained is expected to augment scientific understanding related to: nutrient loss due to agricultural burning; its impact on air quality and health; environmental modeling studies; and climate change studies, apart from supplementing global and regional emission budgeting with reduced uncertainties and policy measures related to FBCR in the region.

Agricultural residue generation and use pattern

The amount of agricultural waste generated varies depending on crop management, crop type, cultivar, region, amendment used, etc. For example two varieties of rice 'IR 20' and 'PHB 71' showed 1.9 (Solaiappan et al. 1996) and 0.9 (Om et al. 1999) 'straw to grain ratios', respectively. Cereal crop show between 0.6 and 2.5 (Ponnamperuma 1984; Barnard 1990), and wetland rice cultivated under a moderate level of management in Philippines show 0.6 and 0.9 (Ponnamperuma 1984) 'straw to grain ratios'.

The primary end-uses of crop residue in India are as animal fodder, industrial/domestic fuel, thatching, packaging, bedding, wall construction, and green-manuring/composting/in situ incorporation. The amounts left out of these pathways are available for field burning. However, only a fraction of this amount is actually subject to field burning. This fraction is in-fact highly variable and uncertain depending upon the factors like livestock distribution, availability of fuel wood, availability of fodder, weed infestation, climate, season etc.

The major residue generating crops with their residue types and use pattern have been discussed here. *Rice* gives two types of residue, straw and husk. Rice straw is major portion of the rice crop residue and is used as fodder mainly for cattle in southern and eastern India and for roof thatching all over the country (Meshram 2002). However it is also subjected to field burning, a practice that is most common in northern part of the country (Meshram 2002). Husk is a byproduct of rice milling and is the second largest agro industrial residue after bagasse produced in the country, up to 43% of which is consumed in rice mills (Meshram 2002). Although husk is not considered fit as fodder due to high silica content, about 5% of it is used as cattle feed (TIFAC 1991). The major share of husk goes as fuel in parboiling rice mills (Tyagi 1989) followed by applications like domestic fuel, bedding for animals especially poultry and also for oil extraction (Tyagi 1989; TIFAC 1991). Husk is generally not subjected to open burning, however introduction of combined harvesters have started to leave husk also in the field that is subjected to burning. *Wheat* straw is produced in large quantity and the major share goes into cattle feeding, domestic fuel, paperboard making and oil extraction (TIFAC 1991; Meshram 2002). Burning of straw is also the easiest and most economical option practiced by farmers to get rid of it in the short period available between two crops in the rice and wheat growing regions of Punjab, Haryana, Uttaranchal and western Uttar Pradesh. *Cotton* stalk, hull and ball, almost all of that could be collected, is used primarily as household fuel (Tyagi 1989; Meshram 2002), whereas, Gin waste is used as fuel in brick making and small industries (Meshram 2002). Some of cotton stalk find its use in fencing, thatching and wall construction and rest is left in field (CIAE 2000). *Sugarcane* produces three types of residues viz. trash, tops and bagasse. Trash is mainly used as fuel in gur making (Tyagi 1989) and to some extent as cattlefeed (Meshram 2002), however a large part goes to open field burning (Meshram 2002). Sugarcane tops are used as fodder partly, but due to low nutritive value is not considered good for animal-feed (Tyagi 1989). Bagasse produced from cane juice extraction is almost completely used up as captive fuel in sugar industry (Tyagi 1989) and none is subject to field burning. *Maize* produces two types of residues viz. sticks/straw and cobs. Sticks/straw is mainly used as fodder and rural domestic fuel. Maize cobs, being hard, are not consumed in significant quantities by livestock as fodder (TIFAC 1991; Meshram 2002). It is either burnt as rural fuel (TIFAC 1991) or thrown away, some of which may be considered to end up in open burning. *Millets* stalk and stick form its residues and is used as fodder and as domestic fuel (TIFAC 1991; Meshram 2002). *Groundnut* stem is used almost completely as domestic fuel (TIFAC 1991). Groundnut shell due to fiber is not fit as fodder hence, mostly end up as industrial fuel (Tyagi 1989; Meshram 2002). Haulms are used as household fuel (Meshram 2002). *Jute* produces two types of residues viz. straw/sticks and dust. Straw/sticks is partly used as fuel in households and tobacco leaves processing (TIFAC 1991; Meshram 2002). Jute dust is used mainly as fuel in boilers and rest is either thrown or collected for household use (Tyagi 1989). *Rapeseed and mustard* (R and M) Stalk is widely burnt in rural domestic chulhas (Tyagi 1989).

Methodology

The CH_4, CO, N_2O and NO_x emission estimates are based on IPCC methodology (IPCC 1995), that is based on 'total carbon released', which is a function of the amount and efficiency of biomass burned and the carbon content of the biomass, and the application of 'emission ratios' of CH_4 and CO to total carbon released, and of N_2O and NO_x to total nitrogen released from the biomass burning (IPCC 1995). It involves different steps viz. calculating the amount of residue, dry residue, total biomass burned, the total carbon released, total nitrogen released, and finally emissions of CH_4, CO, N_2O and NO_x. NO_2 has been used as the reference molecule for NO_x. Various steps of calculations using "activity data" and various "factors" along with associated uncertainties are discussed below:

Activity data

Activity data are the crop or grain production (P) data for the financial years (FY) from 1979 to 1980 through 2009–2010 [ASG (MoA, GoI); and CMIE 2001]. The FY starts from April 1st of the year to March 31st of the following year. The FY data have been mathematically converted to those for the corresponding calendar year (CY). For example, production data from FY 1989–1990 and 1990–1991 have been converted to that of calendar year 1990 using the relationship “Crop Production for (CY) 1990 = ¼ (Crop Production for FY 1989–1990) + ¾ (Crop Production for FY 1990–1991)”. The conversion is based on the assumption that the crop production has been evenly distributed throughout a financial year, and hence this assumption can introduce some uncertainty. The production figures for the period 2006 through 2010 are projections based on the compounded annual growth rates (CAGR) of the crop production data of the period 1996 through 2005.

Conversion factors

The various factors used at different stages of the estimation have been discussed here. *Residue to crop ratio* (RCR) is the ratio of the crop residue generated to that of the main produce. A detail study for rice and wheat crop residues were undertaken for determining these ratio from harvest index (or straw yield) through data from various experimental studies in India (personal communication). Different RCRs for each crop has been used in the present inventory (Table 1). For crops other than rice and wheat, values available from published sources have been used (Table 1). *Dry matter Fraction (DMF)* accounts for the moisture content of the residue during harvesting. *Fraction burned (FB)* is the fraction of the total dry crop residue that is subject to field burning as compared to its other uses (Gupta et al. 2004a). This fraction has been assumed as 0.25, as also recommended (IPCC 1996) for developing countries, for all crops except for maize cobs where a value of 0.2 (Bhattacharya and Mitra, 1998) has been used. *Fraction actually oxidized* (FAO) accounts for the fraction of the biomass that is not oxidized and left back on the field after burning. *Carbon fraction* (CF) accounts for the carbon content of the biomass. *Nitrogen Carbon Ratio* (NCR) is the ratio of nitrogen to carbon of the biomass that is used to find the total nitrogen emitted. *Emission Ratio* (ER) is the ratios for carbon compounds, i.e., CH_4 and CO, released as C relative to mass of total carbon released from burning, and those for the nitrogen compounds are expressed as the ratios of mass of nitrogen compounds released relative to the total mass of nitrogen released from the fuel. *Conversion Ratio* (CR) is the molecular weight ratio to convert the carbon and nitrogen values to full molecular weights of concerned emission species (ES). IPCC (1996) suggests various default values for these factors. However, it is desirable to use region/country specific values for these factors to make the estimates representative. Therefore, India specific values have been used to the extent possible. Table 1 gives the conversion factors used in the present study, along with their sources.

Table 1 Conversion factors for different crop residues used in the emission estimates

	RCR	DMF	FB	FO	CF	NCR	ER	CR
Rice	1.29 ± 0.29[a]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.4144[b]	0.014[b]		
Wheat	1.5 ± 0.25[a]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.4853[b]	0.012[b]	CH_4-0.005 (0.003–0.007)[b]	
Cotton	3[c]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.5[b]	0.015[b]		
Sugarcane	0.1[d]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.5[b]	0.015[b]	CO-0.06 (0.04–0.08)[b]	CH_4-16/12
Maize	0.3[d]	0.4 (0.3–0.5)[b]	0.20[e]	0.9[b]	0.4709[b]	0.02[b]		CO-28/12
Millets	1.2[f]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.5[b]	0.016[b]	N_2O-0.007 (0.005–0.009)[b]	N_2O-44/28
Groundnut	2[f]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.4853[b]	0.015[b]		NO_X-46/14
Jute	2.15[f]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.5[b]	0.015[b]	NO_X-0.121 (0.094–0.148)	
Rapeseed and Mustard	1.8[d]	0.83 (0.78–0.88)[b]	0.25[c]	0.9[b]	0.5[b]	0.015[b]		

[a] Personal communication

[b] (IPCC-1996)

[c] Assumption

[d] Tyagi (1989)

[e] Bhattacharya and Mitra (1998)

[f] TIFAC (Technology Information Forcasting and Assessment Council) (1991)

The overall emissions calculation may thus be summarized as the equation (1) below;

$$E(Gg)=\sum\nolimits_{crops}(P \times RCR \times DMF \times FB \times FAO \times CF \times ER \times CR) \quad (1)$$

where, E = total emissions; Rest of the variables have their usual meanings as described earlier. [for N_2O & NO_x emissions, NRC (as described earlier) is also multiplied before multiplying to respective ERs and CRs; ERs and CRs are specific for each ES (Table 1)].

Uncertainty estimation

The present estimates are among the first efforts related to FBCR emission estimated for India, hence large uncertainties are anticipated. In order to raise the significance level of the estimates, efforts for uncertainty quantification have been undertaken in the present work. The major steps or factors used in the estimation that contribute to uncertainty, in decreasing order of importance, may be listed as FB, RCR, DMF and P followed by the ER of the different gases. The FB is the most uncertain and critical factor that has considerable influence on the net emissions from this source. RCR depends on various factors e.g., water regimes, climatic-seasonal variations, cultivars, soil types and agricultural practices. The DMF (or moisture content of the residue at the time of burning) varies widely with cultivar, climate, environment etc. and lack of relevant information contributes to this uncertainty. The P values are compiled by the Ministry of Agriculture (Government of India); however, some uncertainty may be anticipated whose magnitude might differ with region depending upon the mode of data collection and calculation. The ERs of the various gases are highly environment dependent and may vary widely with burning temperature, crop characteristics and other environmental factors. Uncertainties associated with the above factors have been collected from various sources and used to calculate standard and combined uncertainties in the estimates. The uncertainty calculation methodology has been adopted from the Eurachem guide (Eurachem 2000), that is discussed briefly below. Here, as the confidence levels for most of the variables are not available, a normal (rectangular) distribution has been assumed in all the uncertainty calculations. The first step involves identifying major uncertainty sources that may be listed as P, RCR, DMF, FB and ER. The second step is to calculate the standard uncertainty (u) of each uncertainty source identified in step 1. In case, the standard deviation is available for a variable (as given in Table 1), it is directly taken as 'u'. In case of variables for which ranges are available (Table 1), the difference of the mid-value with the minimum/maximum is utilized to find 'u' based on the Eq. (2) given below:

$$u(X)=x\Big/\left(3^{1/2}\right) \quad (2)$$

u(X) = standard uncertainty in variables like P, RCR, DMF, etc. x = difference between mid-values and minimum/maximum of the range.

In case of variables for which no uncertainties are available, values based on expert judgment of 0.1, 10 and 40%, respectively for P, RCR and FB have been considered, for which 'u' is calculated based on Eq. (3).

$$u(X)=[(y/100)*X]\Big/\left(3^{1/2}\right) \quad (3)$$

where, y = percentage variation

The 'u' calculated for the different variables have been presented in Table 2. After calculation of 'u', the third step involves calculation of combined uncertainty (Uc) for the final emission estimates of each ES and for each crop residue type based on Eq. (4)

$$Uc(Ez) = E\left\{[u(P)/P]^2+[u(RCR)/RCR]^2+[u(DMF)/DMF]^2+[u(FB)/FB]^2+\left[u(ERa)/ERa]^2\right]\right\}^{1/2} \quad (4)$$

where, Ez = emission for different crop residues; ERa = emission ratios of the respective ES (Table 1).

The fourth and final step is to calculate the final combined uncertainty (Ufc) for total Indian FBCR emissions (for all the nine crop residue types taken together) for each ES. Since the total emission for all the nine crops is a simple addition of the emissions for the different crops, the Ufc is calculated based on Eq. (5)

$$Ufc\ (E)=\left[Uc(Er_1)^2 + Uc(Er_2)^2 + Uc(Er_3)^2 + \ldots\right]^{1/2} \quad (5)$$

where, Ufc (E) = final combined uncertainty in emission estimates for all crop residue types for each ES; $Uc(ER_i)$ = combined uncertainty in emission estimates of each crop residue type.

Table 2 Standard uncertainties (u) in the various conversion factors (that are major contributor to uncertainties) used in the emission estimation for different crop residue types

	Rice	Wheat	Cotton	Sugarcane	Maize	Millets	Groundnut	Jute	R and M
P	26.0909	18.9081	0.7583	77.6758	3.3209	2.5305	3.3937	0.6414	0.8868
RCR	0.2900	0.2500	0.1732	0.0058	0.0173	0.0693	0.1155	0.1241	0.1039
DMF	0.0289	0.0289	0.0289	0.0289	0.0577	0.0289	0.0289	0.0289	0.0289
FB	0.0577	0.0577	0.0577	0.0577	0.0462	0.0577	0.0577	0.0577	0.0577
CH_4 ER	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
CO ER	0.0115	0.0115	0.0115	0.0115	0.0115	0.0115	0.0115	0.0115	0.0115
N_2O ER	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
NO_x ER	0.0156	0.0156	0.0156	0.0156	0.0156	0.0156	0.0156	0.0156	0.0156

There may be uncertainty associated with other factors used in the estimation e.g. CF, NCR etc., however, they are expected to be relatively smaller as compared to those of the earlier discussed factors and have been assumed to be negligible.

The conversion factors used in this paper have been sourced from the available literature including IPCC data base as well as based on personal communication with relevant experts as referred to in Table 1.The kind of research is very scarce in the region which pose major constraint in uncertainty estimation as well.

Results and discussion

Residue generation

Based on annual crop production, area covered, residue generation, cropping practice, use pattern, etc., nine major crops viz. rice, wheat, cotton, sugarcane, maize, millets (finger and small), groundnut, jute, and rapeseed and mustard (R & M), have been identified as significant crops for contributing to the FBCR emissions in India, that have been considered in the present study. Table 3 gives the annual amount of residue generation, along with estimated combined uncertainties (Eurachem 2000), for the years 1980, 1985, 1990, 1994, 2000, 2005 and 2010, whereas Fig. 1 shows the percentage contribution of the major crops to the total dry residue generated in India for the period 1980 through 2010. It is observed that the rice, wheat and sugarcane are the major contributors to the total dry residue generation in India i.e., about 40, 33 and 10% during the three decades, respectively. There has been significant increase in the amount of residue generated between 1980 through 2010 for rice (89%), wheat (112%), cotton (232%), sugarcane (132%), Maize (139%) and R & M (249%).

Table 3 Dry residue generation estimates (along with combined uncertainties) for different crops for the years 1980, 1985, 1990, 1994, 2000, 2005 and 2010 for India (Tg)

Crops	1980	1985	1990	1994	2000	2005	2010
Rice	54.2 ± 17.6	66.7 ± 21.7	79.1 ± 25.7	87.0 ± 28.2	91.9 ± 29.9	95.7 ± 31.1	102.4 ± 33.2
Wheat	42.2 ± 7.2	55.6 ± 9.5	64.6 ± 11.0	77.1 ± 13.1	84.6 ± 14.4	83.0 ± 14.1	89.7 ± 15.3
Sugarcane	11.8 ± 0.8	13.6 ± 0.9	19.0 ± 1.3	21.1 ± 1.4	23.9 ± 1.6	21.6 ± 1.5	26.2 ± 1.8
Groundnut	8.3 ± 0.6	8.7 ± 5.9	12.3 ± 0.8	12.8 ± 0.9	9.6 ± 0.6	12.3 ± 0.9	7.9 ± 0.5
Millets	3.9 ± 0.3	3.6 ± 0.2	3.5 ± 0.2	3.1 ± 0.2	2.9 ± 0.2	2.7 ± 0.2	1.8 ± 0.1
R & M	3.0 ± 0.2	4.0 ± 0.3	7.1 ± 0.5	8.1 ± 0.5	6.6 ± 0.4	11.5 ± 0.8	10.5 ± 0.7
Cotton	2.9 ± 2.0	3.5 ± 0.2	4.1 ± 0.3	4.7 ± 0.3	4.1 ± 0.3	7.3 ± 0.5	9.7 ± 0.7
Jute	2.0 ± 0.1	3.0 ± 0.2	2.4 ± 0.2	2.4 ± 0.2	22.9 ± 0.2	3.0 ± 0.2	3.3 ± 0.2
Maize	0.8 ± 0.1	0.9 ± 0.1	1.1 ± 0.2	1.1 ± 0.2	1.4 ± 0.2	1.7 ± 0.3	1.9 ± 0.3
Total	**128.6 ± 27.1**	**159.7 ± 33.7**	**192.4 ± 40.1**	**216.7 ± 45.1**	**226.5 ± 47.8**	**239.0 ± 49.4**	**253.3 ± 52.8**

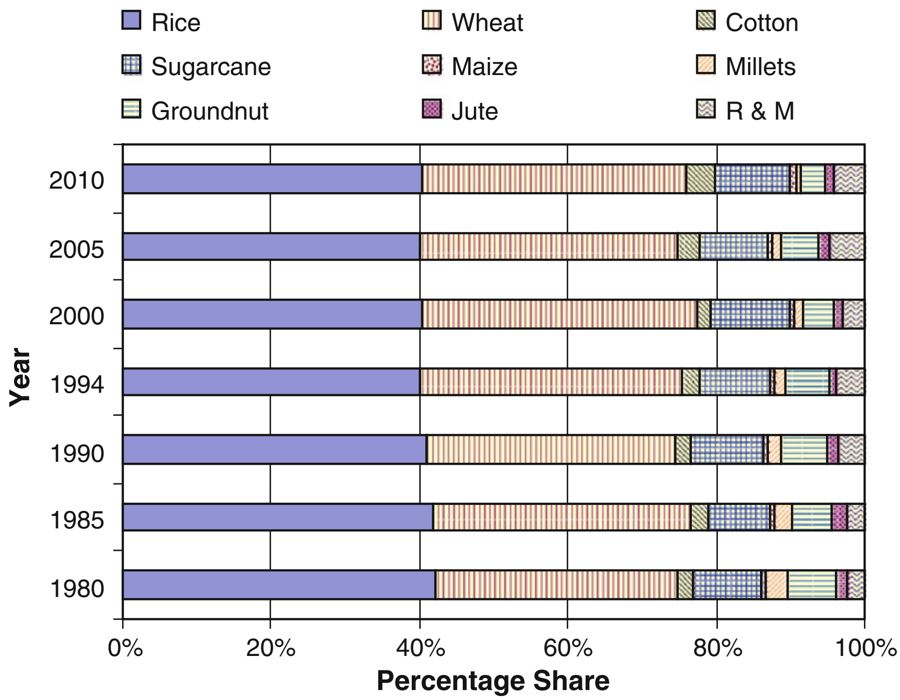

Fig. 1 Shares of different crops in dry residue generation

However, millets and groundnut showed a decline of 54 and 5%, respectively for the period. The overall share of most of the crop residues has remained consistent to some extent over the years (Fig. 1).

The total dry residue generated based on present study has been estimated to increase about 97% between 1980 and 2010, i.e. 129 ± 27, 160 ± 34, 192 ± 40, 217 ± 45, 227 ± 48, 239 ± 49 and 253 ± 53 Tg, respectively for the years 1980, 1985, 1990, 1994, 2000, 2005 and 2010, respectively (Table 3). Others have estimated about 176.9 Tg available residues for 1978–1979 (Singhal and Atreja 1985), 41 Tg available biofuel from crop waste for 1990 (UNEDR 1993–1994), and 169.8 and 267.7 Tg of agricultural biomass potential for years 1980–1981 and 1994–1995 (TEDDY 1997), respectively for India. The substantial difference may be mainly attributed to the different residue to crop ratios used, and the inclusion of different crops in other studies because of the special emphasis on residue for energy use.

Wheat, rice, cotton, sugarcane and groundnut comprise major residue generating crops in the country (Table 3) that are important for FBCR. Wheat and rice together accounted for about 76% in the different years, viz. 164 and 179 Tg for the years 1994 and 2000, respectively. The state-wise scenario for 1994 and 2005 shows that, incase of rice straw, Uttar Pradesh (U.P), Punjab, Haryana, West Bengal (W.B), Orissa, Andhra Pradesh (A.P.) and Bihar states together generated about 67% (87 Tg) and 69% (95 Tg) of the total rice straw, respectively. In case of wheat straw, U.P, Punjab, Madhya Pradesh (M.P), Haryana, Rajasthan and Bihar together generated about 92% (77 Tg) and 91% (83 Tg) of the total dry straw in years 1994 and 2005, respectively. In case of sugarcane trash U.P, Maharashtra, Tamil Nadu (T.N), Karnataka, A.P, Gujarat, Haryana, Bihar and Punjab together generated about 98% (21 Tg) and 97% (22 Tg) of the total dry trash giving a potential 4.4 and 4.9 Tg dry trash estimate for field burning in 1994 and 2005, respectively. Lack of information on fraction of residue actually subject to FBCR is the main constraint, hence IPCC (1995) suggested fraction (0.25) for developing countries has been applied for all the crop residues except for Maize cobs for which a value of 0.2 (Bhattacharya and Mitra 1998) has been used, and finally 32, 48, 45, 57, 60 and 63 Tg of total (all crops) dry biomass are estimated to be subjected to field burning in years 1980, 1985, 1990, 1994, 2000, 2005 and 2010, respectively. It should be mentioned here that anticipating wide variations in this factor (FB) and based on expert judgment, an

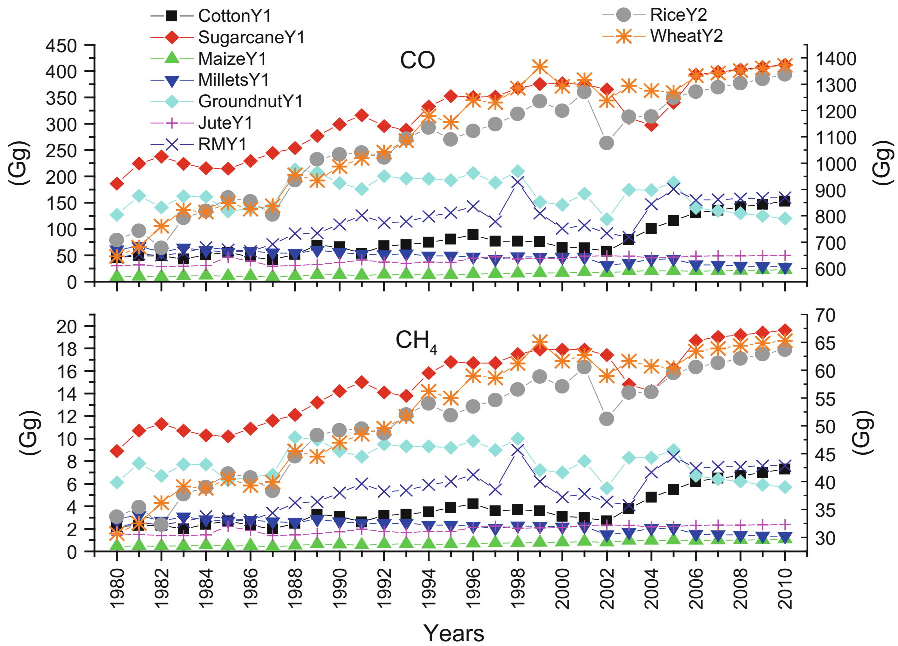

Fig. 2 Crop-wise variation of CH_4 and CO emission between 1980 and 2010 from FBCR in India. [both the graphs have common legends; emissions for rice and wheat are shown on Y2 axis (Gg)]

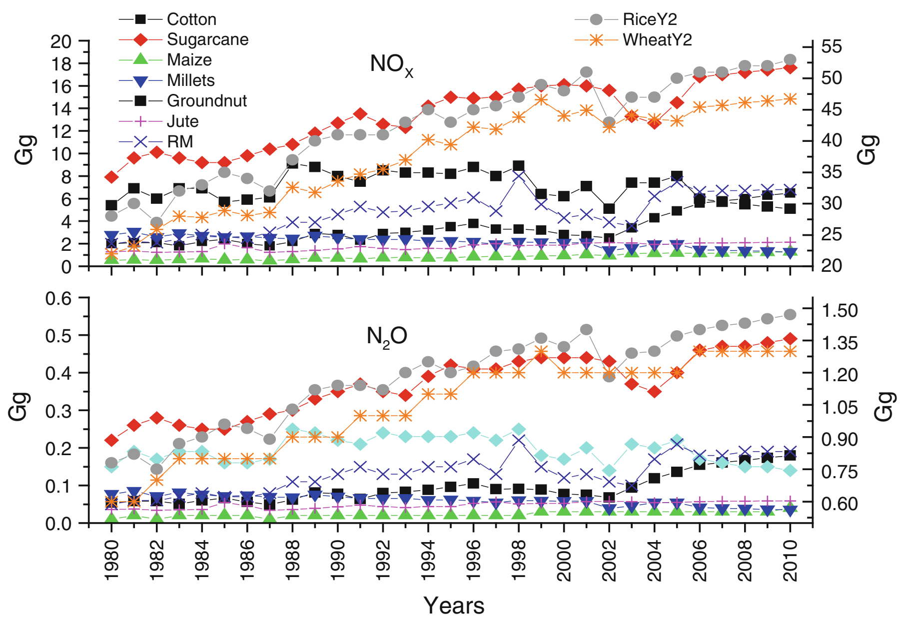

Fig. 3 Crop-wise variation of N_2O and NO_X emission between 1980 and 2010 from FBCR in India. [both the graphs have common legends; emissions for rice and wheat are shown on Y2 axis (all in Gg)]

uncertainty of ± 10% (as described in Sect. 3.3) has been considered with this factor in the present study. On relating the present findings with those of Streets et al. (2003), it is observed that in the year 2000, Indian FBCR contributed about 8 and 4% of the non-biofuel biomass and the total biomass burning of Asia, and about 44 and 14% of those of India, respectively. Based on the same comparison it has been found that Indian FBCR contributed about 23% to the Asian crop-residue burning in the year 2000.

There are some significant uncertainties in the estimates related to crop to residue ratio, fraction subject to field burning, dry matter fraction and fraction oxidized, whose quantification and reduction will be very useful. Of the various uncertainty sources identified in the study, 'fraction burned' and

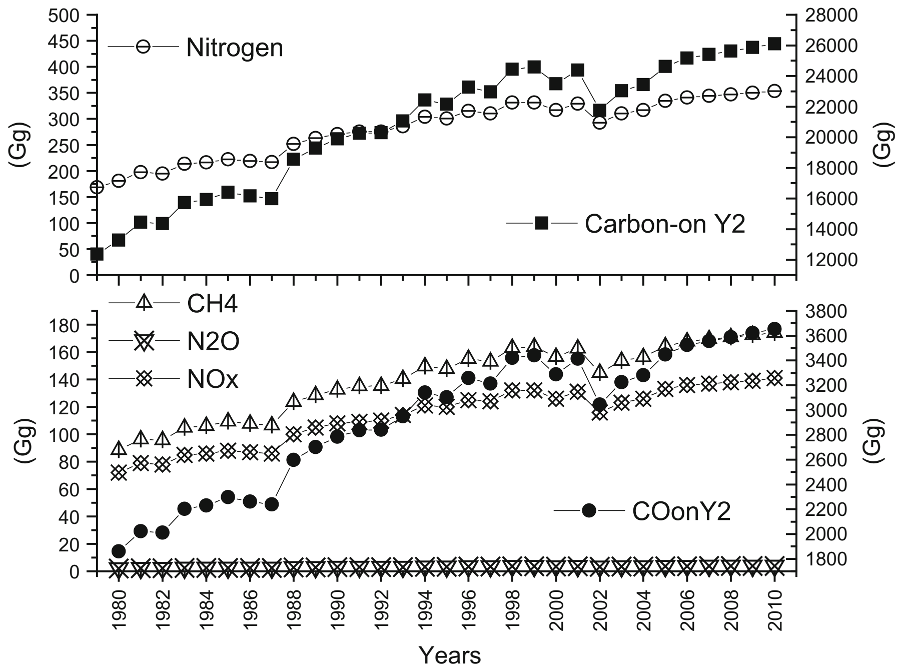

Fig. 4 Emission of trace gases (CH_4, N_2O, NO_X and CO), total nitrogen and total carbon from FBCR of all the nine crops between 1980 and 2010 in India (CO and carbon on Y2 axis; all in Gg)

'residue to crop ratio' are the most significant sources. This is firstly because of their maximum contribution to uncertainty and secondly, because they have maximum reduction potential. In the present work, efforts have been made to address these two uncertainties by focusing on rice and wheat, the two major crops that contribute almost 70% in the present estimates.

Trace gas emissions

Most of the crops show a gradual increasing trend in their residue production (Table 3) and hence increase in trace gas emissions over the three decades has also been observed (Figs. 2, 3 and 4). The variations in the emission estimates due to other factors like land-use change etc. cannot be ascertained due to lack of availability of relevant information in India. FBCR emission under wheat showed higher growth rate[1] (3.65%) as compared to that of rice (3.07%). Residue of sugarcane (3.85%), *R* and *M* (6.14%), maize (4.24%), cotton (5.88%) and Jute (2.42%) have also shown significant growth. However, the emissions from millets and groundnut crop residue have shown negative growth rate of 3.65 and 0.27%. The states of U.P, Punjab, M.P, W.B, A.P, Haryana, T.N., Bihar, Rajasthan, Maharashtra, Gujarat and Karnataka in decreasing order are the major Indian states contributing to trace gas emission from FBCR in the years 1994, 2000 and 2005 (Figs. 5, 6). However, Punjab and Haryana states, considering their comparatively small areas, are the biggest concern due to large emissions (Figs. 5, 6). Also it is important to mention that among the different ES, the combined uncertainty was observed to be highest in case of CH_4 as a result of maximum percentage variation in its ER i.e. 40% (Table 1).

The total GHG (CH_4 and N_2O) in terms of carbon dioxide equivalent [CDE; using global warming potential values of 23 for CH_4 and 296 for N_2O (TAR 2006)] has been estimated to be about 4.4 ± 0.7, 4.6 ± 0.8, 4.9 ± 0.8 and 5.2 ± 0.9 Tg CDE in the years 1994, 2000, 2005 and 2010, respectively. Figures 7a and b give further detailed crop-wise inventory of the trace gas emissions in terms of CDE for the years 1994, 2000, 2005 and 2010. CH_4-CDE formed over 77% of the total FBCR CDE emissions of GHG (Fig. 7b). Rice straw, wheat straw and sugarcane trash are the major crop residue types contributing about 80–85% of the Indian FBCR emissions (Fig. 7). The FBCR CDE emissions contributed over 1% of the total of that from the Indian

[1] Compond Annaual Growth Rate.

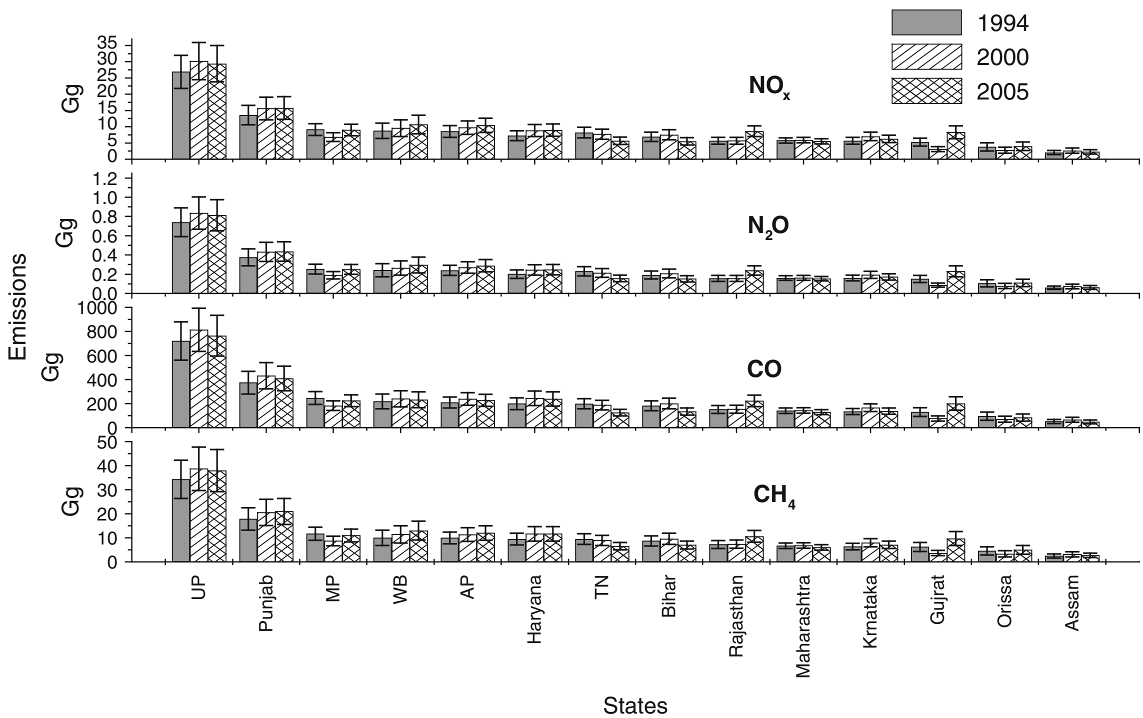

Fig. 5 CH_4, CO, N_2O and NO_x emission (error bars represent the combined uncertainty in emission estimates for all nine major crops) from FBCR for major contributor states of India in the years 1994, 2000 and 2005 (Gg)

agriculture sector in the year 1994 on comparison with NATCOM (2004) values.

Methane (CH_4)

The FBCR in India in the year 2000 contributed an estimated 1.8% and 13.6% of the Asian and Indian CH_4 emissions from all types of biomass burning, taking into account the estimates of Streets et al. (2003). The total Indian FBCR CH_4 emissions are estimated as 88.6, 132.7, 149.6, 156.4, 164.2 and 174.0 Gg for the years 1980, 1990, 1994, 2000, 2005 and 2010, respectively (Figs. 2, 4; Table 4). Rice, wheat and sugarcane together accounted for about 73.3, 110.4, 126.0, 136.6, 136.1 and 148.6 Gg in the years 1980, 1990, 1994, 2000, 2005 and 2010, respectively. Bhattacharya and Mitra (1998) estimated 144.6 Gg CH_4 emissions for the year 1990 for this source. The major share in emissions from the main crops i.e. rice, wheat and sugarcane from major states in the year 1994 and 2005 have also been estimated (Fig. 2). For example, for rice, out of the total Indian emission of 54.1 and 59.5 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 36.1 and 41 Gg; for wheat, out of the total Indian emission of 56.2 and 60.4 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 51.9 and 55.3 Gg; and for sugarcane, out of the total Indian emission of 15.8 and 16.2 Gg, the states of U.P, Punjab, Haryana, W.B, Orissa, A.P. and Bihar together contributed 15.5 and 15.8 Gg, respectively (Figs. 5, 6).

Carbon monoxide (CO)

The FBCR in 2000 contributed an estimated 1.8 and 10.0% of the Asian and Indian CO emissions from all types of biomass burning, taking into account the estimates of Streets et al. (2003). The total Indian FBCR CO emissions have been estimated as 1742, 2614, 2952, 3084, 3240 and 3431 Gg for years 1980, 1990, 1994, 2000, 2005 and 2010, respectively (Figs. 2, 4; Table 4). Rice, wheat and sugarcane together accounted for 1422, 2147, 2458, 2669, 2650 and 2897 Gg emissions of CO in the years 1980, 1990, 1994, 2000, 2005 and 2010, respectively.

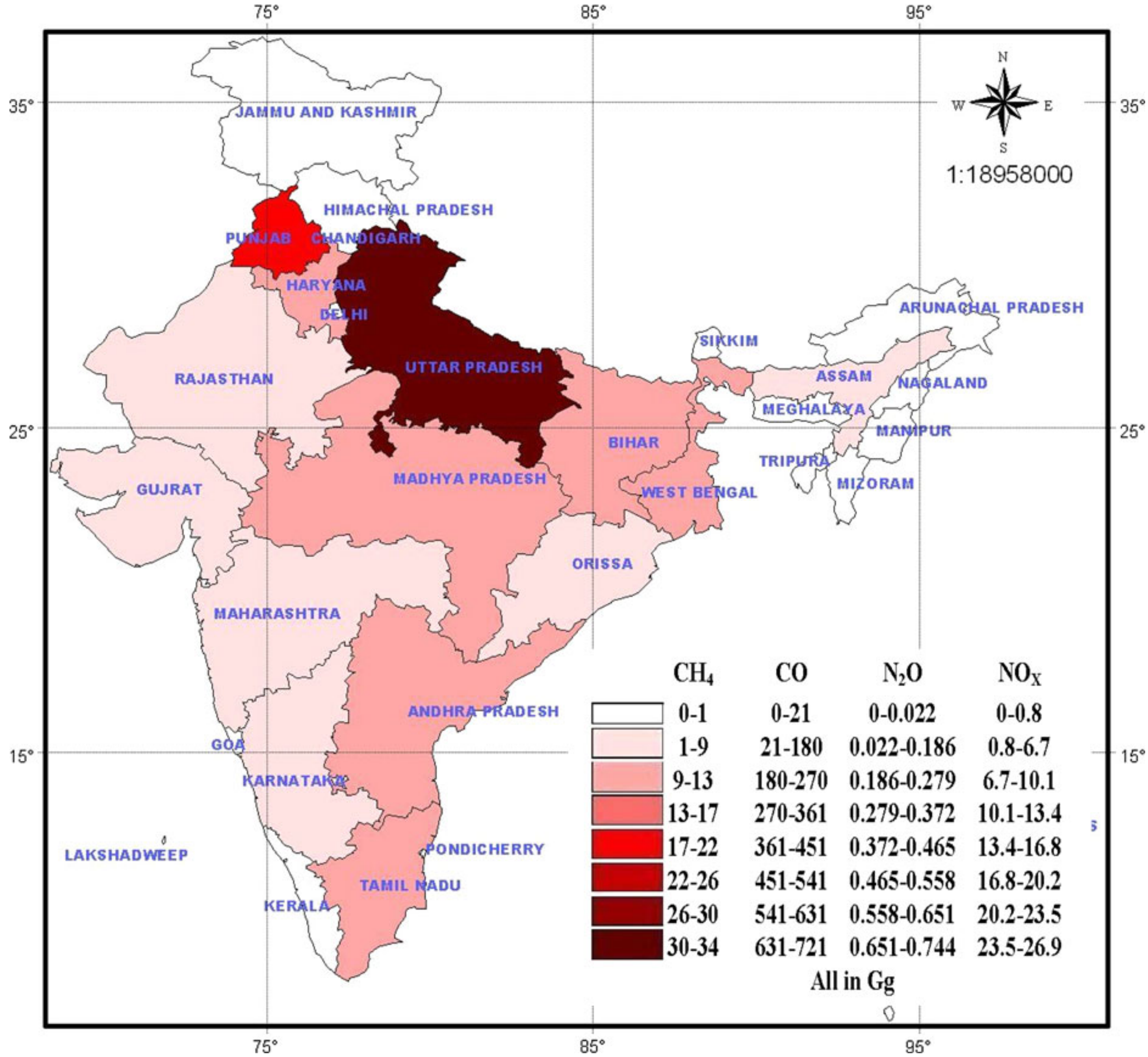

Fig. 6 State-wise emission of CH_4, CO, N_2O and NO_X from FBCR in India for the year 1994 (in Gg)

Bhattacharya and Mitra (1998) estimated 3.04Tg CO emission for the year 1990 from this source. The major share in CO emission from main crops i.e. rice, wheat and sugarcane from major states in the year 1994 and 2005 has been estimated (Fig. 3) which shows that for rice, out of the total Indian emissions of 1135 and 1249 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 759 and 858 Gg; for wheat, out of the total Indian emission of 1179 and 1268 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 1090 and 1160 Gg; for sugarcane, out of the total Indian CO emission of 333 and 340 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 325 and 331 Gg, respectively (Figs. 5, 6).

Nitrous oxide (N_2O)

Streets et al. (2003) have not provided estimates for N_2O emissions. However, the total Indian N_2O emissions under the present study have been estimated as 2.1, 3.0, 3.3, 3.5, 3.7 and 3.9 Gg for 1980, 1990, 1994, 2000, 2005 and 2010, respectively (Figs. 3, 4; Table 4). Rice, wheat and sugarcane together emitted 1.61, 2.42, 2.8, 3.0, 3.0 and 3.2 Gg N_2O in the years

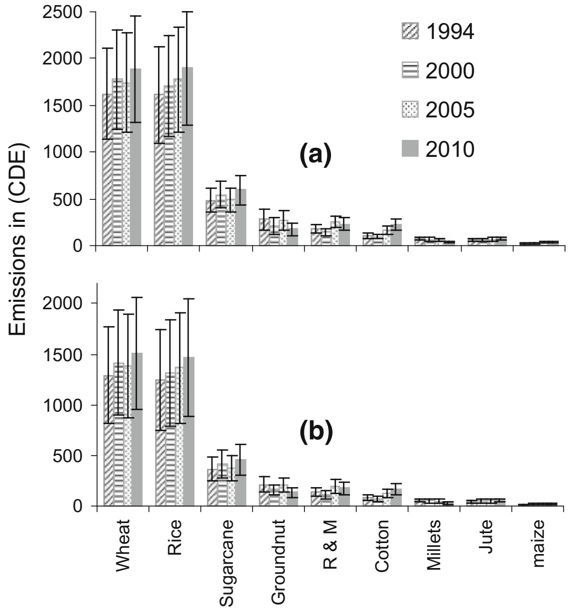

Fig. 7 Emissions estimates in CO_2-equivalent (CDE) units from different crop residue types in the years 1994, 2000, 2005 and 2010 (**a**) total emissions (for CH_4 and N_2O); and (**b**) for CH_4 emissions only

1980, 1990, 1994, 2000, 2005 and 2010, respectively. Bhattacharya and Mitra (1998) estimated 3 Gg N_2O emissions for the year 1990 from this source. The major share in N_2O emission from main crops (Figs. 3, 4) i.e. rice, wheat and sugarcane from major states in the year 1994 and 2005 was also estimated. For rice, out of the total Indian emission of 1.3 and 1.4 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed emission of 0.8 and 0.9 Gg; for wheat, out of the total Indian emissions of 1.1 and 1.2 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 1.0 and 1.1 Gg; and for sugarcane, out of the total Indian N_2O emissions of 0.39 and 0.40 Gg and, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 0.38 and 0.39 Gg, respectively (Figs. 5, 6).

Oxides of nitrogen (NO_x)

The Indian FBCR in 2000 contributed an estimated 1.7 and 8.8% of the Asian and Indian NO_X emissions from all types of biomass burning, taking into account the estimates of Streets et al. (2003). The total Indian NO_x emissions (as NO_2) have been estimated as 72.0, 107.7, 120.8, 125.8, 132.9 and 140.6 Gg for 1980, 1990, 1994, 2000, 2005 and 2010, respectively (Figs. 3, 4; and Table 4). Rice, wheat and sugarcane together emitted about 58.9, 87.4, 99.5, 107.8, 107.4 and 117.4 Gg of NO_x in the years 1980, 1990, 1994, 2000, 2005 and 2010, respectively. Bhattacharya and Mitra (1998) estimated 109Gg NO_x emissions for the year 1990 from the source in India. The major share in NO_x emission from the main crops i.e. rice, wheat and sugarcane from major states in the year 1994 and 2005 (Fig. 3) show that for rice, out of the total Indian emissions of 45.1 and 49.7 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed emission of 30.2 and 34.1 Gg; for wheat, out of the total Indian emissions of 40.2 and 43.2 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 37.2 and 39.5 Gg; and for sugarcane, out of the total Indian NO_x emission of 14.2 and 14.5 Gg, the states of U.P, Punjab, Haryana, W.B., Orissa, A.P. and Bihar together contributed 13.8 and 14.1 Gg, respectively (Figs. 5, 6).

Carbon and nitrogen emissions

Field burning of such large quantities of biomass has been estimated to emit 13.3, 15.5, 19.9, 22.4, 23.5, 24.4 and 26.1 Tg of carbon and, 0.18, 0.21, 0.27, 0.30, 0.32, 0.33 and 0.35 Tg of Nitrogen in the years 1980, 1985, 1990, 1994, 2000, 2005 and 2010, respectively to the atmosphere (Fig. 4). These emissions, however, may not represent net emission to the atmosphere since they have been previously fixed via photosynthesis. Nevertheless these estimates for nitrogen and carbon are useful to understand their biogeochemical cycles.

The uncertainties associated with these estimates can possibly be narrowed down if more accurate information on FB, DMF, FO and ER are available. Hence, a detailed survey covering these gaps for the Indian region is required to be undertaken urgently. Additionally, the alternate pathways for the crop residues that end up in FBCR could primarily be: in situ incorporation; as green manure; as fodder; or as energy source. These alternative pathways are also associated with GHG emission (IPCC 1996; NATCOM 2004); however, the FBCR practice should be discouraged as it results in increasing emission of harmful gases and particulate matters (Sahai et al.

Table 4 Crop-wise emission estimates for CH_4, CO, N_2O and NO_X for the years 1994, 2000, 2005 and 2010 for Indian FBCR [Gg; ± gives the associated combined uncertainties (Ufc)]

Crops	CH_4 (Gg)				N_2O (Gg)			
	1994	2000	2005	2010	1994	2000	2005	2010
Wheat	56.2 ± 20.7	61.55 ± 22.7	60.42 ± 22.3	65.30 ± 24.1	1.11 ± 0.37	1.22 ± 0.40	1.20 ± 0.40	1.29 ± 0.43
Rice	54.0 ± 21.5	57.09 ± 22.7	59.48 ± 23.7	63.65 ± 25.4	1.25 ± 0.45	1.32 ± 0.48	1.37 ± 0.50	1.47 ± 0.54
Sugarcane	15.8 ± 5.3	17.95 ± 6.0	16.21 ± 5.4	19.64 ± 6.6	0.39 ± 0.11	0.44 ± 0.13	0.40 ± 0.12	0.49 ± 0.14
Groundnut	9.3 ± 4.7	6.97 ± 3.5	8. 95 ± 4.5	5.72 ± 2.9	0.23 ± 0.11	0.17 ± 0.08	0.22 ± 0.11	0.14 ± 0.07
Rapeseed and Mustard	5.9 ± 2.0	4.81 ± 1.6	8.38 ± 2.8	7.64 ± 2.6	0.15 ± 0.04	0.12 ± 0.03	0.21 ± 0.06	0.19 ± 0.06
Cotton	3.5 ± 1.2	3.11 ± 1.0	5.50 ± 1.8	7.28 ± 2.4	0.09 ± 0.03	0.08 ± 0.02	0.14 ± 0.04	0.18 ± 0.05
Millets	2.3 ± 0.8	2.18 ± 0.7	2.05 ± 0.7	1.33 ± 0.4	0.06 ± 0.02	0.06 ± 0.02	0.05 ± 0.02	0.04 ± 0.01
Jute	1.8 ± 0.6	2.11 ± 0.7	2.21 ± 0.7	2.38 ± 0.8	0.04 ± 0.01	0.05 ± 0.02	0.05 ± 0.02	0.06 ± 0.02
Maize	0.6 ± 0.2	0.81 ± 0.3	0.99 ± 0.4	1.07 ± 0.4	0.02 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.04 ± 0.01
Total	**149.6 ± 30.8**	**156.58 ± 32.9**	**164.20 ± 33.5**	**174.0 ± 35.9**	**3.34 ± 0.61**	**3.49 ± 0.65**	**3.68 ± 0.66**	**3.9 ± 0.71**
Crops	CO (Gg)				NOx (Gg)			
	1994	2000	2005	2010	1994	2000	2005	2010
Wheat	1179 ± 407.4	1292.61 ± 446.6	1268.92 ± 438.4	1371.20 ± 473.7	40 ± 12.6	44.05 ± 13.9	43.24 ± 13.6	46.73 ± 14.7
Rice	946 ± 428.3	999.13 ± 452.4	1040.98 ± 471.4	1113.84 ± 504.4	45 ± 15.8	47.67 ± 16.7	49.66 ± 17.3	53.14 ± 18.6
Sugarcane	333 ± 102.5	376.95 ± 116.1	340.39 ± 104.9	412.34 ± 127.0	14 ± 3.9	16.06 ± 4.4	14.50 ± 4.0	17.56 ± 4.8
Groundnut	196 ± 95.9	146.27 ± 71.6	187.97 ± 92.0	120.15 ± 58.8	8 ± 3.9	6.23 ± 2.9	8.01 ± 3.8	5.12 ± 2.4
Rapeseed and Mustard	124 ± 38.3	101.04 ± 31.1	176.00 ± 54.2	160.37 ± 49.4	5 ± 1.5	4.30 ± 1.2	7.50 ± 2.1	6.83 ± 1.9
Cotton	75 ± 22.9	65.21 ± 20.1	115.56 ± 35.6	152.94 ± 47.1	3 ± 0.9	2.78 ± 0.8	4.92 ± 1.3	6.51 ± 1.8
Millets	49 ± 15.1	45.88 ± 14.1	42.98 ± 13.2	27.90 ± 8.6	2 ± 0.6	2.08 ± 0.6	1.95 ± 0.5	1.27 ± 0.4
Jute	37 ± 11.4	44.23 ± 13.6	46.51 ± 14.3	50.07 ± 15.4	2 ± 0.4	1.88 ± 0.5	1.98 ± 0.5	2.13 ± 0.6
Maize	13 ± 4.4	16.98 ± 5.7	20.75 ± 7.0	22.55 ± 7.63	1 ± 0.2	0.96 ± 0.3	1.18 ± 0.4	1.28 ± 0.4
Total	**2951.5 ± 609.5**	**3088.29 ± 651.6**	**3240.06 ± 662.2**	**3431.4 ± 709.5**	**120.8 ± 21.0**	**126.02 ± 22.4**	**132.94 ± 22.9**	**140.6 ± 24.4**

2007) and also cause loss of useful resource (Gupta et al. 2004a) which could otherwise be used more effectively and efficiently.

Conclusion

A state-wise and crop-wise resolved inventory of crop residue generation, amount burnt in field and the related emissions of carbon, nitrogen, CH_4, CO, N_2O and NO_x have been estimated for India for the period 1980 through 2010. The nine major crops contributing to FBCR in India generated an estimated 129 ± 27, 217 ± 45 and 239 ± 49 Tg of dry residues, respectively in the years 1980, 1994 and 2005. Indian FBCR emitted about 13.3, 22.4, 24.4 and 26.1 Tg of carbon, and 0.18, 0.30, 0.32, and 0.35 Tg of nitrogen in the years 1980, 1994, 2005 and 2010, respectively, where the estimates for 2006 through 2010 period are based on CAGR of previous year data. This source in 1994 and 2005 emitted 4.18 and 4.59 Tg CDE of GHGs, 2951Gg and 3240Gg of CO, and 1208Gg and 1329Gg of NO_x, respectively, which form almost 1% of those emitted from the agriculture sector in India. U.P, Maharashtra, T.N., Karnataka, A.P., Punjab, Haryana and Bihar states alone accounted for almost 70% to the total emissions, whereas, rice, wheat and sugarcane alone contributed almost 84% of the total emissions. It is, thus, observed that FBCR is a concerning cause of trace gas emissions and subsequent loss of soil nitrogen and carbon in India, which is increasing with mechanization of farming in the affluent regions of the country. The amount of crop residues ending up in FBCR is considerable that can be used as resource. Further, mitigation efforts for such emissions need to be undertaken, by avoidance of field burning and utilization of the crop residue resource, thereby enabling agro-ecosystem sustainability. There are key uncertainty issues to be worked upon, some of which have been addressed in the present study. It may be mentioned here that, the uncertainties associated with 'fraction actually oxidized' can be further reduced if more experimental case studies are undertaken, whereas, future availability of crop specific values may reduce the uncertainties in the 'carbon fraction' estimation. Information on 'moisture content' and 'fraction oxidized' can significantly contribute to improve the estimates, which need to be better accounted in crop statistics. Development of India specific emission factors for the various emission species from FBCR under different crops and climatic zones is highly desirable to improve the emission estimates.

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