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Biomass Burning Sources of Nitrogen Oxides, Carbon Monoxide, and Non-methane Hydrocarbons

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1. Introduction

Biomass burning may significantly change the chemical climatology of our atmosphere. The largest source of dry mass combustion per year is the burning of savannas (Andreae, 1991). However, biomass may also be burned to clear forests for agriculture and grazing, control grass, weeds, and litter, eliminate agricultural waste, and serve as domestic fuels (e.g. wood and dung) (Crutzen and Andreae, 1990; Levine et al., 1995).

Biomass burning is an important source of many key tropospheric species, including aerosols, carbon dioxide (CO_2), nitrogen oxides ($NO_x = NO + NO_2$), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), methyl bromide (CH_3Br) (Mano and Andreae, 1994), ammonia (NH_3), non-methane hydrocarbons (NMHCs) and other species. These emissions and their subsequent products act as pollutants and affect greenhouse warming of the atmosphere. One important by-product of biomass burning is tropospheric ozone, which is a pollutant that also absorbs infrared radiation. Ozone is formed when CO, CH_4, and NMHCs react in the presence of NO_x and sunlight. Ozone concentrations in tropical regions (where the bulk of biomass burning occurs) may increase due to biomass burning (Fishman et al., 1991). Additionally, biomass burning can increase the concentration of nitric acid (HNO_3), a key component of acid rain (Lacaux et al., 1991)

1. a. Combustion stages

Biomass burning has two main phases: flaming and smoldering (Cofer et al., 1990a). During the flaming stage, the fuel is well mixed with the surrounding air, and combustion is rapid and more efficient. The products include oxidized gases such as CO_2, NO_x, and N_2O (Lobert et al., 1991; Laursen, et al., 1992, Ward et al., 1992). Flaming combustion often dominates when grasses burn. Thermal convection and vertical transport can accompany flaming and some smoldering combustion. Aircraft sampling often represents the combined flaming and smoldering products (Hurst et al., 1994b).

The smoldering stage generally has a lower combustion efficiency and lasts much longer. The products include a larger fraction of reduced gases such as CO, CH_4, NMHCs, and NH_3 (Lobert et al., 1991; Laursen et al., 1992, Ward et al., 1992) than is the case for flaming combustion. In a fire that is mainly smoldering, the products tend to remain closer to the ground and, therefore, ground-based sampling may be biased toward smoldering products (Hurst et al., 1994a,b). Forest fires often are primarily smoldering. As noted above, combustion can also be a combination of the flaming and smoldering phases.

1. b. Mathematical description of products

The products of combustion are often expressed in terms of emission factors and excess emission ratios. Emission factors are the ratio of (g compound emitted)/(kg dry matter burned). Excess emissions are usually represented by molar (or sometimes mass) based ratios of the enhancement of concentration above background levels relative to a species such as CO_2, CO, or aerosols (e.g. $\Delta X/\Delta CO_2$). These ratios are unitless. Because of their common source, flaming products are expected to correlate well with the concentration of CO_2. Smoldering products, however, should correlate more closely with the concentration of CO. Although past research has tended to correlate all product concentrations with CO_2, a more realistic interpretation is to correlate with the proper carbon compound of the combustion phase (Lobert et al., 1991; Ward and Hardy, 1991; Ward et al., 1992).

2. Nitrogen oxide emissions from biomass burning

Global biomass burning emission inventories for NO_x are derived in this work by applying NO_x emission factors to global inventories of dry mass combustion. The amount of nitrogen oxides emitted during biomass burning is a strong function of the nitrogen content of the fuel (Clements and McMahon, 1980; Lobert et al., 1991; Hurst et al., 1994a). For biomass, the nitrogen content can vary substantially between fuel types. Dignon et al. (1991) calculated a least squares fit to the Clements and McMahon's (1980) data on emission factors as a function of fuel nitrogen content. The fit is given by:

$$EF(NO_x) = -1.2 + 3.9 n_f \qquad (1.1)$$

where $EF(NO_x)$ is the emission factor of NO_x in (g N)/(kg dry matter burned) and n_f is the percent nitrogen content of the fuel. The linear correlation coefficient of 0.95 is statistically significant at better than the 99 percent confidence interval. Table 1 in Dignon et al. (1991) lists nitrogen fuel content and emission factors calculated using the least squares fit for a variety of fuels. We updated the nitrogen content and emission factors of several fuels as shown in Table 1 below.

Table 1 Calculated emission factors (using Equation 1.1) for nitrogen oxides emitted from biomass burning, (g N/kg Dry Matter)

Fuel type	% Nitrogen content	Calculated EF, g N/kg DM	Reference for % nitrogen content
Tropical forest	1.1	3.1	Dignon et al., 1991
Boreal Forest	0.93	2.4	Lobert et al., 1991
Scrub & grassland*	0.48	0.7	Hurst et al., 1994a; Lobert et al., 1991
Agricultural waste	0.51	0.8	Lobert et al., 1991
Fuelwood & charcoal*	0.23	0.3	Lobert et al., 1991 Crutzen and Andreae, 1990

The emission factors in Table 1 were then applied to the amount of dry matter burned as tropical forests, scrubland, agricultural waste, and fuelwood and charcoal, which were derived by Liousse et al. (1995) and to the amount of boreal forest dry matter burned tabulated by Dignon and Penner, 1991. The emission factors are discussed in more detail below.

2. a. Savannas

Of particular importance are the savannas, since they represent the largest amount of biomass burned per year (Andreae, 1991). Three different estimates of the emission factor were made. Firstly, Dignon et al. (1991) assumed a 0.82% nitrogen content for scrub and grassland, and calculated an emission factor of 2.0g N/kg dry matter using equation (1.1). Secondly, recent measurements of the nitrogen fuel content yielded 0.48% for Australian savanna materials (grass, twigs, and leaves) (Hurst et al., 1994a), 0.48% for Venezuelan grass (Lobert et al., 1991), 0.15% for Australian savanna grass (Lobert et al., 1991), and 0.22 - 0.23% for Ivory Coast savannas (Delmas, 1982). Assuming a nitrogen content of 0.48% in equation (1.1) above yields an emission factor of 0.7 g N/kg dry matter. Additionally, a third emission factor estimate was made. Recent field and laboratory measurements of the fraction of nitrogen in fuel converted to NO_x are 12.7% (Lobert et al., 1990), 15% (Hurst et al, 1994b), and 21% (Hurst et al., 1994a).

Assuming a nitrogen content of 0.48% (4.8 g nitrogen per kg of dry matter), yielded an emission factor of 0.6, 0.7, and 1 g N/kg dry matter for the three conversion factors above, respectively. Based on the above estimates, an emission factor for 0.7 g N/kg dry matter is used in the savanna calculations.

2. b. Tropical forests

For tropical forests, the calculated emission factor of 3.1 gN/kg dry matter from Dignon et al. (1991) was used.

2. c. Fuelwood and charcoal

The emission factor for fuelwood and charcoal is not obtained using equation (1.1) due to the low nitrogen content of fuelwood. Lobert et al. (1991) measured a nitrogen content of 0.23% and a carbon content of 48.3% for deciduous wood. Bhatt and Todaria (1990) measured the nitrogen content of 33 different fuelwoods (mountain trees and shrubs). The average nitrogen content was 0.36%. Usually between 10 to 20% of fuel nitrogen is emitted as NO_x. Assuming Crutzen and Andreae's (1990) conversion of 12.1% of fuel nitrogen to NO_x, and a fuel nitrogen content of 0.23% yielded an emission factor of 0.3 g N/kg dry matter, which is shown in Table 1.

2. d. Agricultural waste

Agricultural waste was assumed to be a combination of straw, deciduous wood, and hay, with nitrogen contents of 0.19%, 0.23%, and 1.12%, respectively (Lobert et al., 1991). The agricultural waste nitrogen content was taken to be an average, or 0.51% nitrogen. Using equation (1.1), an emission factor of 0.8 g N emitted/kg dry matter burned was calculated.

2. e. Boreal forests

The emission of NO_x from boreal forests was calculated using three different methods. The first method employed emission factors for boreal fires calculated by Hegg et al. (1990) and Laursen et al. (1992). For two boreal fires (Battersby and Hardiman), Hegg et al. (1990) calculated emission factors of 1.05 and 3.3 g NO_x/kg dry matter. Laursen et al. (1992) calculated emission factors of 2.5, 2.7, 0.3, 0.37, 1.6 and 2.6 g NO_x/kg dry matter. We used a midrange of these values: 1.8 g NO_x/kg dry matter. Based on the total dry matter burned in forests with latitudes greater than 25 degrees (Dignon and Penner, 1991), this yielded a global estimate of 0.02 Tg N released per year by boreal fires.

The second method used an average emission ratio of $\Delta NO_x/\Delta CO_2 = 0.001$ based on six boreal fires (Laursen et al., 1992). Assuming that roughly 90% of the fuel C was coverted to CO_2, gave an estimate of 0.01 Tg NO_2/year released by boreal fires.

The third method used a nitrogen fuel content measured in the laboratory by Lobert et al. (1991) to estimate an emission factor using equation 1.1. Lobert et al. (1991) measured the nitrogen content of needle litter, pine needles, and deciduous wood to be 1.24%, 1.33%, and 0.23%, respectively. An average of these three, 0.93% was used in equation (1.1) to derive an emission factor of 2.4 gN/kg dry matter. Applying this emission factor to the amount of boreal material burned (Dignon and Penner, 1991) yielded a global total of 0.09 Tg N/year. If boreal forests are composed mainly of needle litter, then this estimate will be an upper bound. For our calculations, we assume that a total of 0.05 Tg N/year was burned in boreal fires, with the distribution given by Dignon and Penner, 1991.

The emission factors shown in Table 1 were applied to the amount of dry mass burned on a monthly basis for tropical forests, savannas, agricultural waste, and fuelwood and charcoal tabulated by Liousse et al., 1995. The NO_x emission factor for boreal forests was applied to the amount of dry mass burned in boreal forests tabulated by Dignon and Penner, 1991. Table 2 shows the calculated Tg NO emitted each month for different biomass types. The total amount of NO_x emitted by biomass burning is 13.8 Tg NO/year, or 6.5 Tg N/year.

Table 2. The amount of nitrogen emitted as NO_x by biomass burning on a monthly basis (Tg NO)

Month	Forest	Savanna	Fuelwood & charcoal (undev)	Fuelwood & charcoal (dev)	Agriculture (undev)	Agriculture (dev)	Boreal Forest
1	0.96	0.29	0.030	0.016	0.018		---
2	0.99	0.27	0.030	0.015	0.043		---
3	0.82	0.19	0.029	0.015	0.12		---
4	0.41	0.06	0.029		0.13	0.019	---
5	0.46	0.29	0.035		0.10	0.0096	---
6	0.69	0.61	0.032		0.98		---
7	0.85	0.72	0.033		0.041		---
8	0.91	0.73	0.032		0.043		---
9	0.65	0.44	0.032		0.045	0.0096	---
10	0.32	0.11	0.032	0.015	0.098	0.039	---
11	0.44	0.14	0.026	0.016	0.10	0.019	---
12	0.67	0.23	0.029	0.017	0.11		---
TOTAL	8.2	4.1	0.37	0.094	0.87	0.096	0.11

3. Carbon monoxide emissions from biomass burning

While most of the carbon emitted by fires is in the form of CO_2, roughly 10% of the carbon is emitted as CO. Carbon monoxide is emitted primarily during the smoldering phase of combustion. As with other species, the amount of CO emitted is a function of vegetation type, fuel density, temperature, relative humidity, wind direction and speed, and other factors.

Savanna fires generally burn rapidly and with a high combustion efficiency. They can be accompanied by high temperatures and convection. The smoldering phase of a savanna fire may last only several minutes (Hao and Ward, 1993). Savanna CO emissions, therefore, are relatively low. Additionally, aircraft sampling may both capture the integrated flaming and smoldering savanna CO emissions because the fire may result in strong convection (Hurst et al., 1994a).

The smoldering phase for other vegetation such as tropical forests lasts for a few hours to a few days (Hao and Ward, 1993), resulting in more CO emissions. Little convection may be associated with these fires, and ground based sampling may be biased toward smoldering (and, therefore, CO) emissions. Fuelwood is often burned under fuel-rich conditions and at low combustion efficiencies. Its CO emissions can be appreciable.

Because both species are emitted during fires, CO data is often reported as an excess emission ratio relative to CO_2. Values of the CO emission factor (g CO emitted/kg dry matter burned) as a function of vegetation type are also reported. Thirdly, the fraction of fuel C emitted as CO is also reported. Below, we apply both **molar-based** excess emission ratios of $\Delta CO/\Delta CO_2$ and emission factors (g CO emitted/kg dry matter burned) to the total amount of savannas, tropical forests, agricultural waste, and fuelwood and charcoal burned (Liousse et al., 1995) as well as to the total amount of boreal forests burned (Dignon and Penner, 1991) The results are summarized in Table 3.

3. a. Savannas

3. a. 1.) Excess emission ratio

Savanna fires have been studied both in the laboratory and field. Greenberg et al. (1984) estimated a mean excess emission ratio of 11.3% ($\Delta CO/\Delta CO_2$) during ground and aircraft based sampling of grassland fires in Brazil. Excess emissions from west African savannas of 11.04% ($\Delta CO/\Delta CO_2$) were measured on the ground by Bonsang et al. (1991). Aircraft sampling in southern African savannas measured an average excess emission ratio of 6.7% ($\Delta CO/\Delta CO_2$) (Le Canut et al., 1995, Table 3), not including sugar cane fields. Aircraft sampling by Hurst et al. (1994b) yielded an excess emission ratio of 5.8% ($\Delta CO/\Delta CO_2$) for periods of vigorous burning in Australian savanna with large plumes. However, when they measured Australian savanna fire emissions from ignition through flameout, (resulting in a greater proportion of smoldering

combustion), the excess emission ratio was 9.0% (Hurst et al., 1994a). Lobert et al. (1991) measured excess emissions from laboratory savanna combustion to be 6.1% ($\Delta CO/\Delta CO_2$). Hao and Ward (1993) calculated an excess emission ratio of 4.4% based on tower measurements by Ward et al. (1992) over Brazilian savannas. Kaufman et al. (1992) measured an excess emission ratio of 2.2% (1.4% on a mass basis) for one fire in the Amazon that had an extremely high combustion efficiency (and, therefore, low CO emissions). Hurst et al. (1994a) argue that aircraft samples best represent the integrated emissions of flaming and smoldering combustion of savannas. We, therefore, calculated an average excess emission ratio of 7.8% ($\Delta CO/\Delta CO_2$) by averaging all of the above savanna measurements except by Kaufman et al. (1992), which was for just one fire. This method yielded a total savanna source of 210 Tg CO/year.

3. a. 2.) Emission factor

Fewer measurements of the CO emission factor for savanna fires exist. Ward et al. (1992) calculated an emission factor of 58 g CO/kg dry matter for platform sampling of three Brazilian savanna fires during BASE-B. Assuming that the fuel is 46% C and 0.078 of fuel C is released as CO for Australian savanna fires yields an emission factor of 84 g CO/kg dry matter burned for observations by Hurst et al. (1994a). We used an average of these two factors, 71 g CO emitted/kg dry matter burned for our emission factor for savannas, giving a total savanna source of 190 Tg CO/year.

3. b. Tropical forests

3. b. 1.) Excess emission ratio

Forest fires are a smoldering phenomena and have higher rates of CO emissions than savannas. Excess emission ratio measurements include a $\Delta CO/\Delta CO_2$ of 11.9% for ground based sampling in Brazil (Greenberg et al., 1984). Aircraft sampling by Andreae et al. (1988) over Brazilian forests found $\Delta CO/\Delta CO_2 = 8.5\%$. Kaufman et al. (1992) also measured an excess emission factor of $\Delta CO/\Delta CO_2 = 8.5\%$ during aircraft sampling over the Amazon as part of the BASE-A experiment. For tropical forests in the Yucatan Peninsula of Mexico, Cofer et al. (1993) measured an excess emission factor of 7.1% using aircraft. Hao and Ward (1993) calculated an excess emission ratio of 12.4% based on emissions from two Amazon fires (Ward et al., 1992) using surface towers. Because tropical forests can smolder for hours to days (Hao and Ward, 1993), we calculated an excess emission factor of 12.2% by averaging ground- and tower-based observations. This method yielded a total forest source of 140 Tg CO/year.

3. b. 2.) Emission factor

Limited data for emission factors exist for tropical forests. During platform sampling as part of the Brazilian BASE-B campaign, Ward et al. (1992) calculated an emission factor of 91 g CO emitted/kg dry matter burned for a secondary growth forest, and 135 g CO emitted/kg dry matter burned for a primary growth forest. Aircraft sampling by Kaufman et al. (1992) of three tropical forest fires during BASE-A over the Amazon produced emission factors of 47, 98, and 121 g CO emitted/kg dry matter burned, respectively. Because forest fires usually burn in the smoldering phase, we use an average of the tower based sampling of Ward et al. (1992), 113 g CO emitted/kg dry matter burned, for our calculations. This method also yielded a total forest source of 140 Tg CO/year.

3. c. Fuelwood

3. c. 1.) Excess emission ratio

Fuelwood is usually burned under fuel rich conditions (Hao and Ward, 1993). This results in a low combustion efficiency, and higher emissions of CO, CH_4, and NMHCs. Crutzen et al. (1979) cite an excess emission ratio of 18.0% for wood burning in fireplaces (based on work by Short, 1974). Smith et al. (1993) calculate an overall mean of 10% for an excess emission ratio of $\Delta CO/\Delta CO_2$, based on a total of 9 samples from 3 different wood-burning stove fires. They also calculate a weighted excess emission ratio of 9%. We used an excess emission ratio of 10% based on Smith et al (1993), and calculated that 14 Tg CO/year are emitted from developed countries and 51 Tg CO/year from developing countries, for a total of 65 Tg CO/year.

3. c. 2.) Emission factor

Smith et al. (1993) calculate an emission factor of 100 g CO emitted/kg dry matter burned, which we used in our calculations. This resulted in 15 Tg CO/year from developed countries and 57 Tg CO/year from developing countries, for a total of 72 Tg CO/year.

3. d. Agricultural waste

3. d. 1.) Excess emission ratio

Few measurements of excess emission ratios exist for the burning of agricultural waste. Laursen et al. (1992) cite an average of 7.9% ($\Delta CO/\Delta CO_2$) on a molar basis (or 5.0% on a mass basis), following from the work of Darley et al. (1966) and Boubel et al. (1969). Hao and Ward (1993) calculated a molar emission ratio of 8.2% ($\Delta CO/\Delta CO_2$) for agricultural wastes based on a subset of 11 fires studied by Lobert et al. (1991). We used the average of these two measurements, or 8.1% for $\Delta CO/\Delta CO_2$, and calculated that 4 Tg CO/year are emitted by

developed countries, and 37 Tg CO/year are emitted by developing countries, for a total of 41 Tg CO/year.

3. e. Boreal forests

3. e. 1.) Excess emission ratio

Few measurements of emissions from boreal forest fires exist. Cofer et al. (1990b, 1991) calculated excess emission ratios based on three boreal fires: Thomas, Peterlong, and Tyranite. They measured average excess emission ratios of 6.6, 10.1, and 12.3 during the flaming, mixed, and smoldering phases. Assuming that 90% of fuel C is converted to CO_2, and applying an excess emission ratio of 10.1% yielded a total global CO emission of 5 Tg CO/year.

Table 3. CO emission from biomass burning calculated using two methods: (1) Emission factor (g CO emitted/kg dry matter burned) and (2) Excess emission ratio, $\Delta CO/\Delta CO_2$.

Biomass Type	Emission factor method		Excess emission ratio method	
Biomass Type	Emission factor, g CO/kg d.m.	Annual source, Tg CO/year	Excess emission ratio, $\Delta CO/\Delta CO_2$, %	Annual source, Tg CO/year
Savanna	71	190	7.8	210
Tropical Forest	113	140	12.2	140
Fuelwood & charcoal - Developed countries	100	15	10	14
Fuelwood & charcoal - Developing countries	100	57	10	51
Fuelwood & charcoal - TOTAL	100	72	10	65
Agricultural waste - Developed countries	---	---	8.1	4
Agricultural waste - Developing countries	---	---	8.1	37
Agricultural waste - TOTAL	---	---	8.1	41
Boreal forest	117	5	10.1	5
TOTAL SOURCE, Tg CO/yr	---	---		461

3. e. 2.) Emission factor

Hegg et al. (1990) measured an average emission factor of 129 g CO/kg dry matter for two boreal fires. Laursen et al. (1992) measured an average emission factor of 105 g CO/kg dry matter, based on six boreal fires. Using an average of these two emission factors (117 g CO/kg dry matter), we calculated a total global CO emission of 5 Tg CO/year, identical to that obtained by the excess emission ratio method.

4. Non-methane hydrocarbon emissions from biomass burning

A small fraction of the carbon in biomass is emitted as non-methane hydrocarbons during combustion. However, these emissions may elevate substantially to the local non-methane hydrocarbon concentrations, and affect local and regional levels. Excess emission ratios are used to calculate the emissions of NMHCs from the burning of savannas and tropical forests. Emission factors are used to calculate the amount of NMHCs emitted during the combustion of fuelwood and agricultural waste. Because it is such a small source of carbon, the emissions of NMHCs from boreal forests were not included. The total amounts of non-methane hydrocarbons emitted during biomass burning are shown in Table 6. Our calculated total ethane source of 6.3 Tg/year is very similar to the recent estimate of 6.4 Tg/year by Rudolph (1995).

4. a. Savannas

The excess emission ratios for burning of savannas were obtained by averaging the CO_2-normalized molar emission ratios of Bonsang et al. (1991) for African savannas, and Greenberg et al. (1984) for South American savannas. They are shown in Table 4. The excess emission ratios of Hurst et al. (1994b) for Australian savannas were not used because they were for periods of vigorous burning and NMHCs are expected to be emitted mainly during smoldering conditions. When Hurst et al. (1994a) examined, in another study, burning of savannas from ignition through flame out, their CO values increased. It is expected that their NMHC levels probably increased also, as both CO and NMHCs are products of smoldering combustion.

4. b. Tropical forests

For tropical forests, the excess emission ratios of Greenberg et al. (1984) for South American tropical forests were used. They are shown in Table 4, also.

4. c. Fuelwood

Very limited information about fuelwood emissions of NMHCs exists. It was assumed that the emissions would be similar to those emitted by smoldering Ponderosa Pine sapwood, which

were summarized by McKenzie et al. (1994). We used their emission factors of 0.4 g/kg dry matter for ethane and 2.2 g/kg dry matter for ethene. The total emissions of 2.5 g/kg dry matter is similar to the value of 2.5 g/kg dry matter for all NMHC emissions cited by Crutzen et al. (1979). Values are shown in Table 5.

4. d. Agricultural waste

The emissions of NMHCs from the burning of agricultural waste is assumed to be an average of those measured by Darley et al. (1966) and Boubel et al. (1969). The ethene emission factor was 0.9 g ethene/kg dry matter. We assumed that the olefin emission factor was 1.5 g/kg dry matter, comprised of 50% propene and 50% butene. The alkane emission factor is 0.8 g/kg dry matter, split equally between ethane and propane. Values are shown in Table 5.

Table 4. Excess Emission Ratios used for Burning of Savannas and Tropical Forests

Vegetation	Species	CO_2-normalized excess emission ratio	Total source, Tg species/yr	Reference
Savanna	C_2H_6	0.0014	3.6	Greenberg et al. (1984); Bonsang et al. (1991)
	C_3H_8	0.0003	1.2	"
	C_4H_{10}	0.0002	1.1	"
	C_2H_4	0.003	7.2	"
	C_3H_6	0.0011	4.8	"
	C_4H_8	0.0008	3.6	"
Tropical forest	C_2H_6	0.00181	2.2	Greenberg et al. (1984)
	C_3H_8	0.00185	3.3	"
	C_4H_{10}	0.00055	1.1	"
	C_2H_4	0.00326	3.9	"
	C_3H_6	0.00138	2.2	"
	C_4H_8	0.00088	2.2	"

Table 5. Emission factors used for non-methane hydrocarbon emissions from biomass burning of fuelwood and agricultural waste, g species/ kg dry matter

Vegetation	Species	Emission factor,	Total source, Tg species/yr	Reference
Fuelwood	C_2H_6	0.4	0.3	McKenzie et al. (1994)
	C_2H_4	2.2	1.6	"
Agricultural waste	C_2H_6	0.4	0.2	Darley et al. (1966), Boubel et al. (1969)
	C_3H_8	0.4	0.2	"
	C_2H_4	0.9	0.5	"
	C_3H_6	0.8	0.5	"
	C_4H_8	0.8	0.5	"

Table 6. Annual non-methane hydrocarbon emissions from biomass burning, in kg species/yr

Species	Savanna	Tropical forest	Fuelwood	Agricultural waste	Total
C_2H_6	3.6	2.2	0.3	0.2	6.3
C_3H_8	1.2	3.3	---	0.2	4.7
C_4H_{10}	1.1	1.1	---	---	2.2
C_2H_4	7.2	3.9	1.6	0.5	13.2
C_3H_6	4.8	2.2	---	0.5	7.5
C_4H_8	3.6	2.2	---	0.5	6.3

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