

Chapter 14

Biomass Burning

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1. Introduction

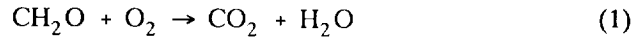
Our planet is a unique object in the solar system due to the presence of a biosphere with its accompanying biomass and the occurrence of fire (Levine, 1991a). The burning of living and dead biomass is a very significant global source of atmospheric gases and particulates. Crutzen and colleagues were the first to assess biomass burning as a source of gases and particulates to the atmosphere (Crutzen et al., 1979; and Seiler and Crutzen, 1980). However, in a recent paper, Crutzen and Andreae (1990) point out that "Studies on the environmental effects of biomass burning have been much neglected until rather recently but are now attracting increased attention." The "increased attention" includes the Chapman Conference on Global Biomass Burning. Much of the information presented here is based on material from this conference (Levine, 1991b). Biomass burning and its environmental implications have also become important research elements of the International Geosphere-Biosphere Program (IGBP) and the International Global Atmospheric Chemistry (IGAC) Project (Prinn, 1991).

The production of atmospheric methane (CH₄) by biomass burning will be assessed. Field measurements and laboratory studies to quantify the emission ratio of methane and other carbon species will be reviewed. The historic database suggests that global biomass burning is increasing with time and is controlled by human activities. Present estimates indicate that biomass burning contributes between about 27 and 80 Teragrams per year (Tg/yr; Tg = 10¹² grams) of methane to the atmosphere. This represents 5 to 15% of the global annual emissions of methane. Measurements do indicate that biomass burning

is the overwhelming source of CH₄ in tropical Africa. However, if the rate of global biomass burning increases at the rate that it has been over the last few decades, then the production of methane from biomass burning may become much more important on a global scale.

2. Gaseous emissions due to biomass burning

Biomass burning includes the combustion of living and dead material in forests, savannas, and agricultural wastes, and the burning of fuel wood. Under the ideal conditions of complete combustion, the burning of biomass material produces carbon dioxide (CO₂) and water vapor (H₂O), according to the reaction:



where CH₂O represents the average composition of biomass material. Since complete combustion is not achieved under any conditions of biomass burning, other carbon species, including carbon monoxide (CO), methane (CH₄), nonmethane hydrocarbons (NMHCs), and particulate carbon, result by the incomplete combustion of biomass material. In addition, nitrogen and sulfur species are produced from the combustion of nitrogen and sulfur in the biomass material.

While CO₂ is the carbon species overwhelmingly produced by biomass burning, its emissions into the atmosphere resulting from the burning of savannas and agricultural wastes are largely balanced by its reincorporation back into biomass via photosynthetic activity within weeks to years after burning. However, CO₂ emissions resulting from the clearing of forests and other carbon combustion products from all biomass sources including CH₄, CO, NMHCs, and particulate carbon, are largely "net" fluxes into the atmosphere since these products are not reincorporated into the biosphere when the land is converted to another use.

Biomass material contains about 40% carbon by weight, with the remainder hydrogen (6.7%) and oxygen (53.3%) (Bowen, 1979). Nitrogen accounts for between 0.3 and 3.8% and sulfur for between 0.1 and 0.9%, depending on the nature of the biomass material (Bowen, 1979). The nature and amount of the combustion products depend on the characteristics of both the fire and the biomass material burned. Hot, dry fires with a good supply of oxygen produce

mostly carbon dioxide with little CO, CH₄, and NMHCs. The flaming phase of the fire approximates complete combustion, while the smoldering phase approximates incomplete combustion, resulting in greater production of CO, CH₄, and NMHCs. The percentage production of CO₂, CO, CH₄, NMHCs, and carbon ash during the flaming and smoldering phases of burning based on laboratory studies is summarized in Table 1 (Lobert et al., 1991). Typically for forest fires, the flaming phase lasts on the order of an hour or less, while the smoldering phase may last up to a day or more, depending on the type of fuel, the fuel moisture content, wind velocity, topography, etc. For savanna grassland and agricultural waste fires, the flaming phase lasts a few minutes and the smoldering phase lasts up to an hour.

Table 1. Percentage of production of CO₂, CO, CH₄, and NMHCs during flaming and smoldering phases of burning based on laboratory experiments (Lobert et al., 1991).

	Percentage in burning stage	
	Flaming	Smoldering
CO ₂	63	37
CO	16	84
CH ₄	27	73
NMHCs	33	67

3. Emission ratios

The total mass of the carbon species (CO₂ + CO + CH₄ + NMHCs + particulate carbon) M_C is related to the mass of the burned biomass (m) by M_C = f × m, where f = mass fraction of carbon in the biomass material, i.e., 40-45%. To quantify the production of gases other than CO₂, we must determine the emission ratio (ER) for each species. The emission ratio for each species is defined as:

$$ER = \frac{\Delta X}{\Delta CO_2} \quad (2)$$

where ΔX is the concentration of the species X produced by biomass burning, and ΔCO₂ is the concentration of CO₂ produced by biomass burning. ΔX = X*

\overline{X} where X^* is the measured concentration of X in the biomass burn smoke plume, and \overline{X} is the background (out of plume) atmospheric concentration of the species. Similarly, $\Delta\text{CO}_2 = \text{CO}_2^* - \overline{\text{CO}_2}$, where CO_2^* is the measured concentration in the biomass burn plume, and $\overline{\text{CO}_2}$ is the background (out of plume) atmospheric concentration of CO_2 .

In general, all species emission factors are normalized with respect to CO_2 , as the concentration of CO_2 produced by biomass burning may be directly related to the amount of biomass material burned by simple stoichiometric considerations as discussed earlier. Furthermore, the measurement of CO_2 in the background atmosphere and in the smoke plume is relatively simple.

For the reasons outlined above, it is most convenient to quantify the combustion products of biomass burning in terms of the species emission ratio (ER). Measurements of the emission ratio for CH_4 and CO normalized with respect to CO_2 for diverse ecosystems (for example, wetlands, chaparral, and boreal; for different phases of burning, flaming, smoldering phases and combined flaming and smoldering phases, called "mixed") are summarized in Table 2. Measurements of the emission ratio for CH_4 normalized with respect to CO_2 for various burning sources in tropical Africa are summarized in Table 3.

Table 2. Emission ratios for CO , CH_4 , and NMHCs for diverse ecosystems (in units of $\Delta X/\Delta\text{CO}_2$, in percent; \pm = standard deviation) (Cofer et al., 1991).

		CO	CH_4	NMHCs
Wetlands	Flaming	4.7 ± 0.8	0.27 ± 0.11	0.39 ± 0.17
	Mixed	5.0 ± 1.1	0.28 ± 0.13	0.45 ± 0.16
	Smoldering	5.4 ± 1.0	0.34 ± 0.12	0.40 ± 0.15
Chaparral	Flaming	5.7 ± 11.6	0.55 ± 0.23	0.52 ± 0.21
	Mixed	5.8 ± 2.4	0.47 ± 0.24	0.46 ± 0.15
	Smoldering	8.2 ± 1.4	0.87 ± 0.23	1.17 ± 0.33
Boreal	Flaming	6.7 ± 1.2	0.64 ± 0.20	0.66 ± 0.26
	Mixed	11.5 ± 2.1	1.12 ± 0.31	1.14 ± 0.27
	Smoldering	12.1 ± 1.9	1.21 ± 0.32	1.08 ± 0.18

Table 3. Emission ratio for CH₄ for different fires in tropical Africa (in units of $\Delta\text{CH}_4/\Delta\text{CO}_2$ in percent; \pm = standard deviation) (Delmas et al., 1991).

Type of Combustion	Emission Ratio = $\Delta\text{CH}_4/\Delta\text{CO}_2$	
	Mean	Range
Natural savanna bushfire	0.28 \pm 0.04	0.23 – 0.34
Forest fire	1.23 \pm 0.60	0.56 – 2.22
Emissions from traditional charcoal oven	2.06 \pm 2.86	6.7 – 14.2
Firewood	1.79 \pm 0.81	1.04 – 3.2
Charcoal	0.14	

Table 4. Average emission factors for CO₂, CO, and CH₄ for diverse ecosystems (in units of grams of combustion product carbon to kilograms of fuel carbon; \pm = standard deviation) (Radke et al., 1991).

	CO ₂	CO	CH ₄
Chaparral-1	1644 \pm 44	74 \pm 16	2.4 \pm 0.15
Chaparral-2	1650 \pm 31	75 \pm 14	3.6 \pm 0.25
Pine, Douglas fir and brush	1626 \pm 39	106 \pm 20	3.0 \pm 0.8
Douglas fir, true fir and hemlock	1637 \pm 103	89 \pm 50	2.6 \pm 1.6
Aspen, paper birch and debris from jack pine	1664 \pm 62	82 \pm 36	1.9 \pm 0.5
Black sage, sumac, and chamise	1748 \pm 11	34 \pm 6	0.9 \pm 0.2
Jack pine, white and black spruce	1508 \pm 16	175 \pm 91	5.6 \pm 1.7
"Chained" and herbicidal paper birch and poplar	1646 \pm 50	90 \pm 21	4.2 \pm 1.3
"Chained" and herbicidal birch, polar and mixed hardwoods	1700 \pm 82	55 \pm 41	3.8 \pm 2.8
Debris from hemlock, deciduous and Douglas fir	1600 \pm 70	83 \pm 37	3.5 \pm 1.9
Overall average	1650 \pm 29	83 \pm 16	3.2 \pm 0.5

Table 5. Emission factors for CO₂, CO, CH₄, and NMHC and ash based on laboratory experiments (in % of fuel carbon; ± = standard deviation) (Lobert et al., 1991).

	Mean	Range
CO ₂	82.58	49.17 – 98.95
CO	5.73	2.83 – 11.19
CH ₄	0.42	0.14 – 0.94
NMHC (as C)	1.18	0.14 – 3.19
Ash (as C)	5.00	0.66 – 22.28
Total sum C	94.91	

Some researchers present their biomass burn emission measurement in the ratio of grams of carbon in the gaseous and particle combustion products to the mass of the carbon in the biomass fuel in kilograms. Average emission factors for CO₂, CO, and CH₄ in these units for diverse ecosystems are summarized in Table 4 and emission factors for CO₂, CO, CH₄, NMHCs, and carbon ash in terms of percentage of fuel carbon based on laboratory experiments are summarized in Table 5. Inspection of Tables 2-5 indicates that there is considerable variability in both the emission ratio and the emission factor for carbon species as a function of ecosystem burning and the phase of burning (flaming or smoldering).

A recent compilation of CO₂-normalized emission ratios for carbon species is listed in Table 6. This table gives the range for both field measurements and laboratory studies and provides a "best guess."

Table 6. CO₂-Normalized emission ratios for carbon species: summary of field measurements and laboratory studies (in units of grams C in each species per kilograms of C in CO₂) (Andreae, 1991).

	Field Measurements	Laboratory Studies	"Best Guess"
CO	6.5 – 140	59 – 105	100
CH ₄	6.2 – 16	11 – 16	11
NMHCs	6.6 – 11.0	3.4 – 6.8	7
Particulate organic carbon (including elemental carbon)	7.9 – 54		20
Element carbon (black soot)	2.2 – 16		5.4

4. Emission of methane

Once the mass of the burned biomass (M) and the species emission ratios (ER) are known, the gaseous and particulate species produced by biomass combustion may be calculated. The mass of the burned biomass (M) is related to the area (A) burned in a particular ecosystem by the following relationship (Seiler and Crutzen, 1980):

$$M = A \times B \times \alpha \times \beta \quad (3)$$

where B is the average biomass material per unit area in the particular ecosystem (g/m^2), α is the fraction of the average above-ground biomass relative to the total average biomass B , and β is the burning efficiency of the above-ground biomass. Parameters B , α , and β vary with the particular ecosystem under study and are determined by assessing the total biomass before and after burning.

The total area burned during a fire may be assessed using satellite data. Recent reviews have considered the extent and geographical distribution of biomass burning from a variety of space platforms: astronaut photography (Wood and Nelson, 1991), the NOAA polar orbiting Advanced Very High Resolution Radiometer (AVHRR) (Brustet et al., 1991a; Cahoon et al., 1991; Robinson, 1991a, 1991b), the Geostationary Operational Environmental Satellite (GOES) Visible Infrared Spin Scan Radiometer Atmospheric Sounder (VAS) (Menzel et al., 1991); and the Landsat Thematic Mapper (TM) (Brustet et al., 1991b).

Hence, the contribution of biomass burning to the total global budget of methane or any other species depends on a variety of ecosystem and fire parameters, including the particular ecosystem that is burning (which determines the parameters B , α and β), the mass consumed during burning, the nature of combustion (complete vs. incomplete), the phase of combustion (flaming vs. smoldering), and knowledge of how the species emission factors (EF) vary with changing fire conditions in various ecosystems. The contribution of biomass burning to the global budgets of any particular species depends on precise knowledge of all these parameters. While all these parameters are known imprecisely, the largest uncertainty is probably associated with the total mass (M) consumed during biomass burning on an annual basis (and there are large year-to-year variations in this parameter!). The total biomass burned annually according to source of burning is summarized in Table 7 (Seiler and Crutzen, 1980; Hao et al., 1990; Crutzen and Andreae, 1990; Andreae, 1991). The

estimate for carbon released of 3940 Tg/yr includes all carbon species produced by biomass combustion ($\text{CO}_2 + \text{CO} + \text{CH}_4 + \text{NMHCs} + \text{particulate carbon}$). About 90% of the released carbon is in the form of CO_2 (about 3550 Tg/yr).

Table 7. Global estimates of annual amount of biomass burning and the resulting release of carbon to the atmosphere (Seiler and Crutzen, 1980; Crutzen and Andreae, 1990; Hao et al., 1990; and Andreae, 1991).

Source of burning	Biomass burned (Tg/yr) ¹	Carbon released (Tg C/yr) ²	CH_4 released (Tg CH_4/yr) ³
Savanna	3690	1660	21.9
Agricultural waste	2020	910	12.0
Fuel wood	1430	640	8.4
Tropical forests	1260	570	7.5
Temperature and boreal forests	280	130	1.7
Charcoal	21	30	0.4
World total	8700	3940	51.9

¹ 1 Tg (teragram) = 10^6 metric tons = 10^{12} grams.

² Based on a carbon content of 45% in the biomass material. In the case of charcoal, the rate of burning has been multiplied by 1.4.

³ Assuming that 90% of the carbon released is in the form of CO_2 and that the "best guess" emission ratio of C: CH_4 to C: CO_2 is 1.1% (see Table 5), and CH_4 (Tg) = C: CH_4 (Tg) * 16/12.

Knowledge of the CO_2 -normalized emission ratio for CH_4 coupled with information on the total production of CO_2 due to biomass burning allows us to estimate the total annual global production of CH_4 due to biomass burning. Field measurements and laboratory studies indicate that the emission ratio for CH_4 is in the range of 6.2 to 16 grams of carbon in the form of CH_4 (C: CH_4) per kilogram of carbon in the form of CO_2 (C: CO_2) (see Table 6), which corresponds to a C: CH_4 to C: CO_2 emission ratio in the range of 0.62 to 1.6%. Using a "best guess" of 1.1% and assuming that biomass burning produces about 3550 Tg/yr of C: CO_2 , then the global annual production of C: CH_4 due to biomass burning is in the range of 21.7 to 56 Tg/yr, which converts to 29 to 75 Tg/yr of CH_4 , with a "best guess" of 52 Tg/yr of CH_4 . The production of CH_4 by

different burning sources on a global scale is summarized in Table 7. A detailed study using a chemical transport model with a $1^\circ \times 1^\circ$ spatial grid yielded an annual average CH_4 production due to biomass burning of 63.4 Tg (Taylor and Zimmerman, 1991), which is somewhat smaller than the maximum CH_4 production value calculated here of 74.7 Tg CH_4/yr . Assuming that the total annual global production of CH_4 from all sources is about 500 Tg CH_4 (Cicerone and Oremland, 1988), then the range of CH_4 we calculate corresponds to between 6% and 15% of the global emissions of CH_4 , while the calculations of Taylor and Zimmerman (1991) suggest that biomass burning produces about 14% of the global emissions of CH_4 . Considering all of the uncertainties in these calculations, there is very good agreement between these two estimates. While an upper limit range of about 15% for the production of methane due to biomass burning may not seem very significant, the importance of this source is enhanced when we consider that the largest single global sources of methane do not produce much more than about 20% of the total.

Delmas et al. (1991) have studied the CH_4 budget of tropical Africa. They considered the emission of CH_4 from biogenic processes in the soil and from biomass burning. They found that the dry African savanna soil is always a net sink for CH_4 . They measured an average soil uptake rate for atmospheric CH_4 of 2×10^{10} CH_4 molecules $\text{cm}^{-2} \text{s}^{-1}$. They calculated the production of CH_4 (and CO_2) due to biomass burning and found that biomass burning supplies about 9.22 Tg CH_4 yr (and 3750 Tg CO_2 yr) (see Table 8). Hence, in tropical Africa, biomass burning, not biogenic emissions from the soil, controls the CH_4 budget.

In addition to the direct production of CH_4 by the combustion of biomass material, there is recent evidence to suggest that burning stimulates biogenic emissions of CH_4 from wetlands. Flux chamber measurements indicate higher fluxes of CH_4 from wetlands following burning. It has been suggested that combustion products, carbon dioxide, carbon monoxide, acetate, and formate entering the wetlands following burning are used by methanogenic bacteria in the metabolic production of CH_4 (Levine et al., 1990).

At present, biomass burning is a significant global source of several important radiatively and chemically active species. Biomass burning may supply 40% of the world's annual gross production of CO_2 or 26% of the world's annual net production of CO_2 (due to the burning of the world's forests) (Seiler and

Crutzen, 1980; Crutzen and Andreae, 1990; Hao et al., 1990; Levine, 1990; Andreae, 1991; Houghton, 1991). Biomass burning supplies 10% of the world's annual production of CH₄, 32% of the CO; 24% of the NMHCs, excluding isoprene and terpenes; 21% of the oxides of nitrogen (nitric oxide and nitrogen dioxide); 25% of the molecular hydrogen (H₂); 22% of the methyl chloride (CH₃Cl); 38% of the precursors that lead to the photochemical production of tropospheric ozone; 39% of the particulate organic carbon (including elemental carbon); and more than 86% of the elemental carbon (Levine, 1990; Andreae, 1991).

Table 8. Total emissions of CO₂ and CH₄ from the burning of biomass in tropical Africa.

Source	Biomass burned ¹	CO ₂ Emission Factor ²	CH ₄ Emission Factor ²	CO ₂ Emissions ³	CH ₄ Emissions ⁴
Savanna bushfires	2.52	1370	1.65	3.45	4.14
Forest fires	0.13	957	6.94	0.12	0.90
Firewood burning	0.12	957	5.42	0.11	0.65
Charcoal production	0.11	641	21.0	0.07	2.31
Total	2.88			3.75	9.22

¹ Biomass burned in units of Gigatons dry matter = 10⁹ metric tons = 10³ Tg = 10¹⁵ grams

² Emission factors units of g gas/kg dry matter

³ CO₂ emissions in units of Gigatons/yr

⁴ CH₄ emissions in units of Teragram/yr

5. *Historic changes in biomass burning*

It is generally accepted that the emissions from biomass burning have increased in recent decades, largely as a result of increasing rates of deforestation in the tropics. Houghton (1991) estimates that gaseous and particulate emissions to the atmosphere due to deforestation have increased by a factor of 3 to 6 over the last 135 years. He also believes that the burning of grasslands, savannas, and

agricultural lands has increased over the last century because rarely burned ecosystems, such as forests, have been converted to frequently burned ecosystems, such as grasslands, savannas, and agricultural lands. In Latin America, the area of grasslands, pastures, and agricultural lands increased by about 50% between 1850 and 1985. The same trend is true for South and Southeast Asia. In summary, Houghton (1991) estimates that total biomass burning may have increased by about 50% since 1850. Most of the increase results from the ever-increasing rates of forest burning, with other contributions of burning (grasslands, savannas, and agricultural lands) having increased by 15% to 40%. The increase in biomass burning is not limited to the tropics. In analyzing 50 years of fire data from the boreal forests of Canada, the U.S.S.R., the Scandinavian countries, and Alaska, Stocks (1991) has reported a dramatic increase in area burned in the 1980s. The largest fire in the recent past destroyed more than 12 million acres of boreal forest in the People's Republic of China and Russia in a period of less than a month in May 1987 (Cahoon et al., 1991).

The historic data indicate that biomass burning has increased with time and that the production of greenhouse gases from biomass burning has increased with time. Furthermore, the bulk of biomass burning is human-initiated. As greenhouse gases build up in the atmosphere and the Earth becomes warmer, there may be an enhanced frequency of fires. The enhanced frequency of fires may prove to be an important positive feedback in a warming Earth. However, it has been suggested that the bulk of biomass burning worldwide may be significantly reduced (Andrasko et al., 1991). Policy options for mitigating biomass burning have been developed by Andrasko et al. (1991). For mitigating burning in the tropical forests, where much of the burning is aimed at land clearing and conversion to agricultural lands, policy options include the marketing of timber as a resource and improved productivity of existing agricultural lands to reduce the need for conversions of forests to agricultural lands. Improved productivity will result from the application of new agricultural technology, e.g., fertilizers. For mitigating burning in tropical savanna grasslands, animal grazing could be replaced by stall feeding since savanna burning results from the need to replace nutrient-poor tall grass with nutrient-rich short grass. For mitigating burning on agricultural lands and croplands, incorporate crop wastes into the soil, instead of burning, as is the present practice throughout the world. The crop wastes could

also be used as fuel for household heating and cooking rather than cutting down and destroying forests for fuel as is presently done.

6. *Uncertainties and future research*

The construction of a global emissions inventory for methane from biomass burning must account for the high degree of variability of these emissions in both space and time. Biomass burning exhibits strong seasonal and geographic variations. As shown earlier, methane emissions from biomass burning are highly dependent on the type of ecosystem being burned, which determines the total amount of biomass consumed and the extent of flaming and smoldering phases during combustion. The calculations by Taylor and Zimmerman (1991) go a long way towards deriving a global inventory in that they have simulated the variability of biomass burning. They scaled the burning rate inversely with precipitation as global data sets are currently not available. Satellite techniques, when they are developed, offer a promising way to obtain global coverage.

Taylor and Zimmerman also used a constant emission ratio in their calculations since measurements of the emission ratio for methane are lacking for many different ecosystems. While some data exist for mid-latitude ecosystems, measurements are needed to better define the contributions from burning tropical forests and savannas. In addition, airborne measurements are limited to the outer edges of biomass burn plumes so little is known about variability across the plume. The use of long path remote measurements across plumes is also planned for the future.

7. *Summary*

Biomass burning may be the overwhelming regional or continental-scale source of CH₄ as in tropical Africa and a significant global source of CH₄. Our best estimate of present methane emissions from biomass burning is about 51.9 Tg/yr, or 10% of the annual methane emissions to the atmosphere. Increased frequency of fires that may result as the Earth warms up may result in increases in this source of atmospheric methane.

It is appropriate to conclude this chapter with an observation of fire historian, Stephen Pyne (1991):

"We are uniquely fire creatures on a uniquely fire planet, and through fire the destiny of humans has bound itself to the destiny of the planet."

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