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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 ($CH_4$) 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 = $10^{12}$ grams) of methane to the atmosphere. This represents 5 to 15% of the global annual emissions of methane. Measurements do indicate that biomass burning

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is the overwhelming source of $CH_4$ 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 ($CO_2$) and water vapor ($H_2O$), according to the reaction:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (1)$$

where $CH_2O$ 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 ($CH_4$), 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 $CO_2$ 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, $CO_2$ emissions resulting from the clearing of forests and other carbon combustion products from all biomass sources including $CH_4$, 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, $CH_4$, and NMHCs. The flaming phase of the fire approximates complete combustion, while the smoldering phase approximates incomplete combustion, resulting in greater production of CO, $CH_4$, and NMHCs. The percentage production of $CO_2$, CO, $CH_4$, 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 $CO_2$, CO, $CH_4$, 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 ($CO_2$ + CO + $CH_4$ + NMHCs + particulate carbon) $M_C$ is related to the mass of the burned biomass (m) by $M_C = f \times m$, where f = mass fraction of carbon in the biomass material, i.e., 40-45%. To quantify the production of gases other than $CO_2$, we must determine the emission ratio (ER) for each species. The emission ratio for each species is defined as:

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

where $\Delta X$ is the concentration of the species X produced by biomass burning, and $\Delta CO_2$ is the concentration of $CO_2$ produced by biomass burning. $\Delta X = X^*$

$- \overline{X}$ 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, $\Delta CO_2 = CO_2^* - \overline{CO_2}$, where $CO_2^*$ is the measured concentration in the biomass burn plume, and $\overline{CO_2}$ 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 $\Delta X/\Delta CO_2$, in percent; ± = 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 $CH_4$ for different fires in tropical Africa (in units of $\Delta CH_4/\Delta CO_2$ in percent; ± = standard deviation) (Delmas et al., 1991).

| Type of Combustion | Emission Ratio = $\Delta CH_4/\Delta CO_2$ | |
|---|---|---|
| | Mean | Range |
| Natural savanna bushfire | 0.28 ± 0.04 | 0.23 – 0.34 |
| Forest fire | 1.23 ± 0.60 | 0.56 – 2.22 |
| Emissions from traditional charcoal oven | 2.06 ± 2.86 | 6.7 – 14.2 |
| Firewood | 1.79 ± 0.81 | 1.04 – 3.2 |
| Charcoal | 0.14 | |

Table 4. Average emission factors for $CO_2$, CO, and $CH_4$ for diverse ecosystems (in units of grams of combustion product carbon to kilograms of fuel carbon; ± = standard deviation) (Radke et al., 1991).

| | $CO_2$ | CO | $CH_4$ |
|---|---|---|---|
| Chaparral-1 | 1644 ± 44 | 74 ± 16 | 2.4 ± 0.15 |
| Chaparral-2 | 1650 ± 31 | 75 ± 14 | 3.6 ± 0.25 |
| Pine, Douglas fir and brush | 1626 ± 39 | 106 ± 20 | 3.0 ± 0.8 |
| Douglas fir, true fir and hemlock | 1637 ± 103 | 89 ± 50 | 2.6 ± 1.6 |
| Aspen, paper birch and debris from jack pine | 1664 ± 62 | 82 ± 36 | 1.9 ± 0.5 |
| Black sage, sumac, and chamise | 1748 ± 11 | 34 ± 6 | 0.9 ± 0.2 |
| Jack pine, white and black spruce | 1508 ± 16 | 175 ± 91 | 5.6 ± 1.7 |
| "Chained" and herbicidal paper birch and poplar | 1646 ± 50 | 90 ± 21 | 4.2 ± 1.3 |
| "Chained" and herbicidal birch, polar and mixed hardwoods | 1700 ± 82 | 55 ± 41 | 3.8 ± 2.8 |
| Debris from hemlock, deciduous and Douglas fir | 1600 ± 70 | 83 ± 37 | 3.5 ± 1.9 |
| Overall average | 1650 ± 29 | 83 ± 16 | 3.2 ± 0.5 |

Table 5. Emission factors for $CO_2$, CO, $CH_4$, 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 $CO_2$, CO, and $CH_4$ in these units for diverse ecosystems are summarized in Table 4 and emission factors for $CO_2$, CO, $CH_4$, 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 $CO_2$-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. $CO_2$-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 $CO_2$) (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):

$$M = A \times B \times \alpha \times \beta \tag{3}$$

where B is the average biomass material per unit area in the particular ecosystem ($g/m^2$), $\alpha$ is the fraction of the average above-ground biomass relative to the total average biomass B, and $\beta$ is the burning efficiency of the above-ground biomass. Parameters B, $\alpha$, and $\beta$ 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, $\alpha$ and $\beta$), 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 ($CO_2$ + CO + $CH_4$ + NMHCs + 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° x 1° 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 $2 \times 10^{10}$ $CH_4$ molecules $cm^{-2}$ $s^{-1}$. 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 $CH_4$, 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 ($H_2$); 22% of the methyl chloride ($CH_3Cl$); 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 $CO_2$ and $CH_4$ 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 = $10^9$ metric tons = $10^3$ Tg = $10^{15}$ grams
2 Emission factors units of g gas/kg dry matter
3 $CO_2$ emissions in units of Gigatons/yr
4 $CH_4$ 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 $CH_4$ as in tropical Africa and a significant global source of $CH_4$. 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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