Biomass Burning: Its History, Use, and Distribution and Its Impact on Environmental Quality and Global Climate

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Pollution from biomass burning was one of the first occupational hazards: early humans must have been exposed to large amounts of carcinogenic compounds from the smoke of open fires in caves, huts, and tents. Today we are frequently confronted with the evidence of pollution from biomass burning in our daily lives: In North America, many communities have had to issue ordinances regulating domestic burning in fireplaces and wood-burning stoves to control atmospheric pollution in winter. In the tropics, airports like Santarém, in the middle of the Amazon Basin, have to be closed frequently during the burning season because of poor visibility resulting from the smoke from gigantic fires hundreds to thousands of kilometers away. Such large fires and the resulting smoke plumes are a common sight to air travelers in the tropics and even to the crews of the Space Shuttle (Figure 1.1).

Despite the magnitude of the problem posed by the emissions from biomass burning, little quantitative information is currently available on the amounts of pollutants emitted and their impact on the environment. In contrast, the effects of fossil fuel burning for heating, energy production, transportation, and so forth have been thoroughly investigated and quantified. This difference may largely be explained by the fact that the production and distribution pathways of fossil fuels are to a large extent under the control of relatively few organizations, either governments or large corporations, and are therefore well known and documented. Biomass burning, on the other hand, takes place to a large extent in the developing countries at the hands of individual farmers, ranchers, and housewives who do not keep records of amounts burned. In this review, I discuss the historical development of biomass burning and its role in agriculture and society and then provide current estimates of the type and amounts of pollutants emitted and their environmental effects.

The History of Fire

Fires must have existed on Earth ever since the evolution of land plants, around 350 to 400 million years ago. The production of plant matter on dry land first made possible the accumulation of "fire potential" in the form of large amounts of combustible organic material. (Some of this accumulated, unburned fire potential from geological times is still present in the form of coal deposits.) Once the production of organic matter by plants had supplied the potential for wildfires, climatic and ecological parameters (length and intensity of dry seasons, lightning frequency, etc.) established a natural fire frequency. The intensity of the resulting wildfires is determined by the combination of the accumulation rate of fire potential and the fire frequency: frequency and intensity are inversely related, a fact that today is well known to foresters and which forms the basis of fire management through prescribed burning.

With the advent of herbivorous organisms, the rate of natural fire potential accumulation became controlled by the interplay of phyto-production on one hand and fire frequency and herbivory on the other (Schüle, 1990). In particular, hypsodont mammals (those with high-crowned teeth, e.g., horses, goats, and camels) are very efficient in removing vegetation in the lower layer of wooded savannas, where fires would normally propagate. Since these grazers are able to consume almost anything, especially small tree seedlings and shoots, they tend to act in the same way as fire in stabilizing savanna-type landscapes. A high rate of grazing by large reptiles (dinosaurs) may have contributed to the predominance of savanna-like vegetation on Earth during the late Cretaceous (about 70 million years ago), which would be accompanied by a high fire frequency and low fire intensity. High concentrations of black carbon (soot and charcoal) in the Cretaceous-Tertiary boundary sediments suggest that the end of the age of dinosaurs was accompanied by large fires which may have perturbed Earth's climate and thereby contributed to the dinosaurs' demise (Wolbach et al., 1985, 1988). In the early Tertiary, almost the entire land surface on Earth was covered with humid forests, where few and relatively ineffective grazers were present. A combination of climate change and the evolution of very large and effective hypsodont mammalian grazers led to

Figure 1.1 Biomass burning in Mozambique, Africa, as seen from the Space Shuttle. The picture was taken on 9 October 1984 by a Space Shuttle astronaut using a hand-held camera (Hasselblad, 70 mm lens). The mouth of the Zambezi River is visible in the center. Large plumes from savanna fires are entrained by easterly winds. Blackened areas from recent fires cover large areas. (Photograph by Space Shuttle Earth Observation Office, NASA)

the spread of savannas and steppes, which became the dominant land vegetation by the end of the Tertiary age. Fire frequency must have changed from very low to very high during this time. These ecological changes contributed to the evolutionary pressures that brought about the development of savanna-living monkeys on one hand and hominids on the other. Eventually, humans overcame the fear of fire common to all other primates and learned to use wildfires, initially as an accidental source of food in the form of insects, rodents, snakes, etc. caught and killed by the fires and later (about 1.5 to 2 million years ago) as an active tool of food preparation, hunting, and landscape control (James, 1989). It is likely that man-made fires began to make an ecological impact in the African savanna at this time.

Early humans thus had to develop quite sophisticated fire-management strategies, examples of which survived up to this century among the Aborigines of Australia (Jones, 1979), where *Homo sapiens* arrived

about 40,000 years ago. At about the same time, pollen records show a shift from pyrophobic vegetation (e.g., *Araucaria* spp.) to pyrotolerant and pyrophilic species (e.g., *Eucalyptus* spp.), and charcoal particles in sediment cores increase by three orders of magnitude. This coincidence suggests the possibility that human use of fire profoundly affected that continent's ecology (Schüle, 1990). More information on the relationship between fire and human evolution can be found in the reviews by James (1989) and Schüle (1990).

On a quantitative level, the history of biomass burning through geological and historical time is difficult to establish, since there is little physical evidence other than charcoal particles buried in sediments. Measurements of charcoal in dated sediment cores have shown some clear correlations between the rate of burning and human activity—for example, the increase of charcoal in Australian sediments coincides with human settlement mentioned above and the shift from wood burning to fossil fuel burning around the turn of the century is recorded in the morphology and number of charcoal and soot particles in Lake Michigan sediments (Griffin and Goldberg, 1979, 1983). Charcoal layers in Amazonian soils also document widespread catastrophic fires during periods of drought in Amazonia in prehistoric times (Sanford et al., 1985). However, much research remains to be done to clarify the relationship between changing human population densities and agricultural-industrial activity on one hand and biomass burning rate on the other.

The Role of Biomass Burning in Agriculture and Economy

In agriculture and economy, biomass burning serves a variety of purposes:

1. clearing of forest and brush land for agricultural use

2. control of brush, weeds, and litter accumulation on grazing and crop lands

3. nutrient regeneration in grazing and crop lands

4. control of fuel accumulation in forests

5. production of charcoal for industrial and domestic use

6. energy production for cooking and heating

Finally there is the category of wildfires, which are not started and controlled by people, but which often have large economic and ecological consequences.

Clearing of Forest and Brush Land
for Agricultural Use

Two approaches to forest clearing for agricultural use may be differentiated: shifting agriculture, which allows the land to return to forest vegetation after a relatively short period of use, and permanent removal of forest, which replaces forest with grazing or crop land. In both instances, the clearing and burning follows initially the same pattern: trees are felled, the vegetation is left to dry out in order to obtain better burning efficiency, and the material is then set on fire, often after bulldozing it together into large piles. The efficiency of this first burn is variable; it often does not exceed 10% to 30% (Fearnside, 1985, 1990). This apparent low efficiency is due to the large fraction of rainforest biomass residing in the tree trunks, only a small portion of which tends to be consumed in the first burn. The remaining material is then moved together into piles and left to rot or dry. It is usually set on fire again when it is judged to be dry enough. As a result of this practice, some 40% of the above-ground carbon from forest clearing enters the atmosphere through combustion, while the rest is released through rotting—that is, microbial decomposition.

In shifting agriculture, which is practiced by some 200 million people worldwide (Seiler and Crutzen, 1980), the cleared area is used for agriculture for a few years and abandoned when yields are felt to be declining; then a new area is cleared. Shifting agriculture is not expected to grow much beyond its present extent, which covers some 300 to 500 million hectares (ha) (Wong, 1978; Sommer, 1976; Seiler and Crutzen, 1980), because virgin forest lands which could be brought into this type of cultivation are becoming more scarce. Instead, lands presently under shifting agriculture are likely to become used for permanent agriculture. Often, however, because of poor soil conditions or land management, the areas become wasteland unsuitable for any type of agricultural use.

The permanent removal of rainforest for agricultural use is rapidly progressing as expanding populations require additional food and living space and as large-scale resettlement programs and land-speculation tactics are implemented. The global rate of deforestation is unclear. Based on work by Lanly (1982), Houghton et al. (1985), and Detwiler et al. (1985), a global deforestation rate of about 22 million ha/yr during the 1970s was estimated by Hao et al. (1990). It must be emphasized that this rate applies to the 1970s and is likely to have increased during the 1980s. Of these 22 million ha/yr, about 7.5 million ha/yr are cleared in virgin rainforest, amounting to an annual destruction of about 0.6% of the approximately 1200 million remaining hectares. Estimates of the fractions of cleared land which go to shifting agriculture and to permanent land use range from 1.9 to 3.4 million and 4.1 to 5.1 million ha/yr, respectively (Lanly, 1982; Detwiler et al., 1985; Houghton et al., 1985; Hao et al., 1990). The discrepancies between the estimates of the fate of land cleared in secondary tropical forest are even greater. Detwiler et al. (1985) estimated that 18 million ha/yr are cleared, all for shifting cultivation. Houghton et al. (1985), on the other hand, calculated that 13.5 million ha/yr were cleared in second-growth forest, of which 10.1 million ha were cleared permanently. This discrepancy remains to be resolved.

Biomass Burning in Tropical Savannas
and Brush Land

Tropical savannas cover an area (1530 million ha) roughly similar to that of the tropical forests (1440 million ha) (Lanly, 1982). These savannas typically consist of a more or less continuous layer of grass with interspersed trees and shrubs. They are burned periodically at intervals which may range from one to three years (Eiten, 1972; Sarmiento and Monasterio, 1975; Lacey et al., 1982; Menaut, 1983). This frequency may be increasing in some regions as a result of growing population and more intensive use of rangeland (Menaut, 1983). While lightning may start some fires in savannas, most investigators are convinced that almost all savanna fires are set by humans. Burning has several objectives: foremost probably is the control of weeds, shrubs, tree seedlings, and litter accumulation. Without burning, the grassy vegetation tends to be overgrown rapidly by shrubs and brush and under many conditions progresses to a chaparral or forest unsuitable for grazing, which is the predominant agricultural use of the grassy savannas. Only the grass and small plants are consumed in the fires; the larger trees are fire-adapted species which suffer little damage and actually thrive under conditions of periodic burning.

Burning is also perceived as a form of pest control because it reduces the population of insects, snakes, and so on. Another reason for burning is the belief that it is an effective way to return the nutrients—stored in the dry vegetation which accumulates during the dry season—to the soils and thereby promote regrowth of fresh grass during the following rainy season. This belief may be fallacious; it is discussed in the section on atmospheric emissions from fires.

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forests, are burned annually to facilitate access and harvest of nonwood forest products (Goldammer, 1988; Stott et al., 1990). Finally, fires are also set to drive game for hunting, a practice which may be one of the earliest uses of fire by humans: The savanna area burned each year is very large: Hao et al. (1990) estimate about 750 million ha, much more than the area burned in tropical rainforests. This applies especially to Africa, where about one-half of the global amount of savanna biomass burning is concentrated.

Fuel Wood and Charcoal

Fuel wood is a major source of energy in the developing countries, and its gathering often represents a large part of the workload of populations in Africa and parts of Asia. About 50% of fuel wood is used for cooking, about 30% for domestic heating, and the remaining 20% for various purposes, such as metalworking and pottery making. Because of the highly distributed nature of firewood gathering and use, the annual amount of wood burning is difficult to estimate. The number given by the Food and Agriculture Organization (FAO) (FAO, 1989) for 1987, 1050 Tg dm/yr (teragrams of dry matter per year; 1 teragram = 1 million tons = 10^{12} grams), is probably an underestimate because it does not cover the use of wood which is not marketed. Table 1.1 shows an estimate based on population and per-capita use statistics, which may be more reliable than the FAO estimate: For the tropical regions, the 1985 population numbers are multiplied by an annual fuel wood consumption of 475 kg per person, based on the discussion in Seiler and Crutzen (1980). This value is actually a conservative estimate of biomass fuel consumption; rural populations consume as much as 1000 kg biomass fuel per person annually (Scurlock and Hall, 1990). Since much of this material is agricultural waste, however, I have included it in that category. These population-based estimates and the FAO statistics agree reasonably well for all continents except Asia, where the domestic use of coal in China and the burning of agricultural wastes may be replacing some fuel wood use. Throughout the developing world, population growth is increasing the demand for firewood, which produces scarcity in some regions. The ensuing calculations adopt a best-guess estimate based on the mean between the FAO and population-based estimates for the developing countries in the tropics and on the FAO data for the developed countries.

Charcoal production for domestic and industrial use has become an important alternative to the direct use of wood as fuel. Transportation of wood from the forest to consumers in the urban areas of the developing countries is cumbersome; therefore, wood is often replaced by charcoal, which has a higher energy density and is thus cheaper to transport. In recent years, large charcoal production plants have been established in countries like Brazil in order to supply charcoal for industrial use, especially for the smelting of pig iron. Often, the wood used in this type of charcoal

Table 1.1 Burning of fuel wood, charcoal, and agricultural waste in tropical and extratropical regions

Region	Population (1985, mill.)[a]	Fuel wood[b]	Fuel wood[c]	Fuel wood (best guess)[d]	Charcoal[c]	Agricultural waste[e]
				Tg dm/yr		
Tropics:						
America	430	180	150	170	7.5	200
Africa	550	240	240	240	9.3	160
Asia	2820	1200	490	850	3.3	990
Oceania	25	11	6	8	0	17
Total tropics	3830	1640	890	1260	20	1360
USA and Canada	260	—	80	80	0.5	250
Western Europe	380	—	40	40	0.2	170
USSR and Eastern Europe	390	—	50	50	0.2	230
World total	4840	—	1050	1430	21	2020

a. FAO (1986).
b. Based on population, a fuel-wood consumption of 475 kg per person per year, and a burning efficiency of 90%.
c. FAO (1989).
d. Mean of population-based and FAO estimate.
e. Based on total production of crops (see text).

manufacture is derived from fast-growing pine plantations. In some of the large projects in the Amazon, however, such as the Grande Carajas Program in the eastern part of the basin, it is anticipated that the wood required for charcoal production will be obtained by clear-cutting the surrounding rainforest. A precedent exists in the state of Minas Gerais, where pig-iron production consumed nearly two-thirds of the state's forests.

Charcoal production consists of the controlled partial combustion (pyrolysis) of dry wood. During this process, a mixture of water, carbon monoxide, methanol, tar, and other volatile products is distilled off, which in principle can be captured and processed into marketable by-products. It is likely, however, that in most of the charcoal kilns in the developing countries these volatile compounds are released to the atmosphere. Depending on the efficiency of the charcoal kiln, the ratio of carbon input (in the form of wood) to carbon output (in the form of charcoal) varies between about 2.0 and 1.2 (Ayres et al., 1987). For the purpose of our estimates of the amount of carbon released into the atmosphere due to charcoal production and use, we have therefore multiplied the amount of charcoal burned by a factor of 1.4 to account for losses during production.

Prescribed Burning and Wildfires in Forests

Wildfires are most common in temperate and boreal forests, since undisturbed tropical forests are usually too moist to allow the propagation of wildfires. According to Brown and Davis (1973), most wildfires are the result of human activities, such as sparks from railroad engines, with only a small fraction (10% to 30%) initiated by lightning. While individual wildfires may be very large and lead to smoke plumes visible over great distances, the area burned per year and the burning efficiency are relatively low. Seiler and Crutzen (1980) estimate that about 3.8 million ha of temperate and boreal forest are subject to wildfires each year.

Prescribed fires are a commonly used tool of forest management, particularly in North America. They serve to reduce the accumulation of dry, combustible plant debris, which is a major cause of destructive wildfires. They are also used to eliminate shrubby vegetation, which competes with tree crops for nutrients. In some regions, prescribed burns are used to maintain particular types of game habitat. Because the practice of prescribed burning is limited to North America and Australia, it has little impact globally but can lead to serious local and regional air pollution.

The area involved has been estimated to be on the order of 2 to 3 million ha/yr (Seiler and Crutzen, 1980).

Burning of Agricultural Wastes

A type of burning which is extremely difficult to quantify because of its distributed nature and because no material of direct economic value is involved is the burning of agricultural wastes, e.g., straw and stubble from grain crops. A very conspicuous source of air pollution in many tropical regions is the burning of sugar-cane fields before harvesting to facilitate the processing of the sugar canes (Kirchhoff et al., 1989). Based on an extrapolation from waste-burning practices in the United States and making some reasonable assumptions about the fraction of agricultural waste burned in developing countries, Seiler and Crutzen (1980) have derived an estimate of 1700 to 2100 Tg dm/yr. Table 1.1 presents a new estimate for this source, based on the FAO crop production statistics for 1985 (FAO, 1986). We have assumed that the amount of agricultural waste is the same as the amount of crops produced, which appears to be reasonable based on the discussion in Seiler and Crutzen (1980). We then assume that 80% of the waste is burned in developing countries (much of it as domestic fuel) and 50% in developed countries, and that the combustion efficiency is 90%. The resulting global estimate is 2020 Tg dm/yr, near the high end of the range suggested by Seiler and Crutzen (1980). It may be important to attempt a careful reexamination of this agricultural waste source, since it appears to be one of the major contributions to atmospheric emissions from biomass burning, and since it has the potential of being reduced substantially by alternative agricultural practices.

Geographical Distribution of Biomass Burning

The geographical distribution of biomass burning is discussed in some detail in the review by Seiler and Crutzen (1980). For the tropics, Hao et al. (1990) have estimated the amount of biomass burning and the resulting emissions in each 5° latitude by 5° longitude grid cell. The results obtained by these authors are summarized in Tables 1.2 and 1.3. Most biomass burning is taking place in the developing countries of the tropics (Tables 1.1 and 1.3), adding an emission of 28 Tg C/yr (from Table 1.1: 20 Tg × 1.4) from charcoal production and combustion to the tropical emissions of 3410 teragrams of carbon per year (Tg C/yr) from forest and savanna burning, fuel wood use, and

Table 1.2 Global estimates of annual amounts of biomass burning and of the resulting release of carbon to the atmosphere

Source	Biomass burned (Tg dm/yr)			Carbon released (Tg/yr)[d]
	Seiler and Crutzen[a]	Hao et al.[b]	Andreae[c]	
Tropical forest	2420	1260	1260	570
Savanna	1190	3690	3690	1660
Temperate and boreal forest	280	—	280	130
Fuel wood	1050	620	1430	640
Charcoal	—	—	21	30
Agricultural waste	1900	660	2020	910
World total	6840	6230	8700	3940

a. Seiler and Crutzen (1980).
b. Hao et al. (1990).
c. This paper: Tropical forest and savanna from Hao et al.; temperate and boreal forest from Seiler and Crutzen; fuel wood, charcoal, and agricultural waste from Table 1.1.
d. Based on a carbon content of 45% in dry biomass. In the case of charcoal, the rate of burning (based on FAO production statistics) has been multiplied by 1.4 to account for losses in the production process (see text).

Table 1.3 Biomass burning in the tropical regions

Region	Forest[a]	Savanna[a]	Fuel wood[b]	Agricultural waste[b]	Region total	
	Tg dm/yr				Tg dm/yr	Tg C/yr
America	590	770	170	200	1730	780
Africa	390	2430	240	160	3210	1450
Asia	280	70	850	990	2190	980
Oceania	—	420	8	17	450	200
Total tropics	1260	3690	1260	1360	7580	3410

a. From Hao et al. (1990).
b. From Table 1.1.

the incineration of agricultural waste, we obtain a total emission of 3440 Tg C/yr from the tropics. This represents 87% of the global emissions from biomass burning (3940 Tg C/yr; Table 1.2). As we will discuss later in the chapter, this is consistent with the observation that the impact of burning on the atmospheric environment appears to be concentrated in the tropics.

An interesting difference between the estimates of Seiler and Crutzen (1980) and Hao et al. (1990) is the relative importance of biomass burning in tropical forests and savannas. In the older study, forest burning was predominant, whereas the more recent work by Hao et al. suggests that savanna burning releases about three times as much carbon to the atmosphere as forest burning. This is especially evident in Africa (Table 1.3), where savanna fires account for almost 90% of the emissions from savanna and forest burning and for almost one-third of the global emissions from

biomass burning. A large proportion of savanna burning in Africa takes place within 15° north and south of the equator. The importance of savanna fires in Africa derives from the large area covered by this landscape type in Africa and the high frequency at which African savannas are burned (about 75% per year). In tropical America, forest burning is concentrated in the Brazilian states of Pará, Maranhão, Goiás, Mato Grosso, and Rondônia (Setzer and Pereira, 1991; Hao et al., 1990). Relatively little forest and savanna burning occurs in tropical Asia, with the exception of Indonesia, Thailand, Malaysia, and India, where rapid deforestation is ongoing (Lanly, 1982; Hao et al., 1990).

Seasonality of Biomass Burning
Frequent mention is made in the literature of "burning seasons," and it is often assumed that practically no burning occurs outside of these periods. Indeed, a

large fraction of the burning of forests and savannas takes place during the dry season, and therefore burning is most intensive in the Northern Hemisphere from December to March and in the Southern Hemisphere from June to September. However, experience in tropical countries shows that burning can be observed almost whenever and wherever there is plant material dry enough to burn. This applies to cooking and heating fires, burning of garden and agricultural wastes, burning of the areas surrounding living quarters to control insects, weeds, and snakes, and often burning just for the pleasure of watching the flames and smoke. Thus, even during the wet season in Amazonia, fires are started along the roads and rivers during short dry spells between rainy days. At the end of the rainy season, many farmers wait for cleared areas to become dry enough to burn, leading to an outbreak of burning in late May and early June in the Southern-Hemisphere part of Brazil. The large-scale forest-clearing burns are usually started later in the dry season in order to have drier fuel and a better burning efficiency. Based on a 1987 satellite survey in Amazonia, Setzer and Pereira (1991) found the highest rate of burning to occur in August and September at the southern perimeter of the Amazon Basin.

Emissions to the Atmosphere from Biomass Burning

Carbon Dioxide

The burning of organic materials produces water vapor and carbon dioxide as the primary products, according to the reaction

$$(CH_2O) + O_2 = CO_2 + H_2O$$
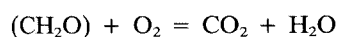
where (CH_2O) stands for the average composition of biological materials. This reaction is essentially the same as the photosynthesis-respiration reaction (photosynthesis from right to left, respiration from left to right). In this sense, biomass burning can be seen as an abiotic equivalent of the respiratory catabolism of biological material, returning the products of photosynthesis back to the atmosphere as CO_2. On a long enough time scale, therefore, biomass burning does not influence the atmospheric CO_2 budget but merely returns to the atmosphere CO_2 that had been removed by plants some time before. This, however, is not as comforting a balance as it at first seems: when biomass is burned and is not rapidly replaced by regrowth, CO_2 is added to the atmosphere and remains there until it is removed by some other process. It can

then contribute to the CO_2 greenhouse effect in the atmosphere and to global climate change.

We must therefore distinguish between gross CO_2 emission from the burning of savannas and forests and the net CO_2 release from deforestation. While prominent in the emission of trace gases to the atmosphere, the periodical burning of savannas has almost no influence on the CO_2 greenhouse effect because the CO_2 released by burning is reincorporated into savanna vegetation during the next growth cycle—i.e., within about one year. In contrast, the clearing of tropical forests by burning contributes directly to the CO_2 greenhouse effect, since the CO_2 emitted from the oxidation of the large amount of biomass stored in a rainforest (as much as 600 tons per hectare, ton/ha) cannot be taken up again by the vegetation which will grow on the same site, usually grass or an agricultural crop. Furthermore, in the case of deforestation, not only does the CO_2 emitted directly by burning contribute to the atmospheric burden, but in most cases the CO_2 released during the decay of the unburned above-ground and below-ground biomass will be greater than that from the burning itself.

The various estimates of the net amount of CO_2 added to the atmosphere from deforestation fall into a relatively narrow range: Houghton et al. (1985) give an estimate of 900 to 2500 Tg C/yr, Detwiler and Hall (1988) suggest a range of 400 to 1600 Tg C/yr, and Hao et al. (1990) calculate 700 to 2000 Tg C/yr. This agreement should not instill undue confidence in the accuracy of these estimates, however. It mostly reflects the fact that all authors base their estimates on the same data: The estimates on land-use conversion by Myers (1980) and by Lanly (1982) and the biomass densities given by Whittaker and Likens (1975), Brown and Lugo (1984), and Detwiler et al. (1985). Hao et al. conclude that almost half of the net CO_2 released comes from the conversion of forest to permanent agriculture and cattle holdings. Other major contributions come from conversion of forests to shifting agriculture, fuel-wood production, and the conversion from virgin to secondary forests. Their calculations suggest that only some 15% of the net CO_2 emission is released immediately during the clearing burns. The remainder is released slowly over the following years either during repeated burning of residual material or through its microbial decomposition. Detwiler and Hall (1988) propose that an additional net CO_2 release of about 25% may result from the oxidation of organic matter in cleared forest soils due to intensive cultivation. Incorporation of this compo-

nent results in an estimate of 1800 ± 800 Tg C/yr for the release of CO_2 from land clearing in the tropics. This is a significant amount compared with the present annual emission of CO_2 from fossil fuel burning— 5200 Tg C/yr. We can therefore conclude that the destruction of tropical forests results in about 25% of the global CO_2 greenhouse effect.

Other Trace Gases

In addition to CO_2 a large variety of other gases and particles are emitted from the fires (Table 1.4); they are the products of incomplete combustion of carbon compounds, such as carbon monoxide (CO), methane (CH_4), and other hydrocarbons, and of compounds containing other nutrient elements, such as nitric oxide (NO) and sulfur dioxide (SO_2), from the nitrogen and sulfur in amino acids and proteins. Particulate matter (aerosol) in the smoke consists of organic matter, black (soot) carbon, and inorganic materials such as potassium carbonate and silica. In fact, the element potassium derives its name from having been isolated from wood-burning ash (potash), where it is present in the form of potassium carbonate. The emission ratios in Table 1.4 are the molar ratio between the species of interest and CO_2 in the smoke, with the exception of the aerosol emission ratios, which are expressed as grams per kilogram (g/kg) $C(CO_2)$. (The ratios have been multiplied by 1000 to make the numbers easier to read.)

Dry plant biomass consists of about 45% carbon (by weight), most of the remainder being hydrogen and oxygen. On a mass basis, the nutrient element contents are relatively low: about 0.3% to 3.8% nitrogen, 0.1% to 0.9% sulfur, 0.01% to 0.3% phosphorus, and 0.5% to 3.4% potassium (Bowen, 1979). Consequently, the emissions from biomass combustion are dominated by the oxides of carbon—CO_2 and CO. The fraction of CO emitted depends on the characteristics of the fire: hot, fast fires with a good supply of oxygen produce relatively little CO, whereas smoldering fires emit a large fraction of this product of incomplete oxidation (Crutzen et al., 1979; Ward, 1986). Pyrolysis and incomplete oxidation in oxygen-deficient fires are also responsible for the emission of CH_4, nonmethane hydrocarbons (NMHC), hydrogen gas (H_2), and various partially oxidized organic compounds, such as alcohols, aldehydes, ketones, and organic acids (Greenberg et al., 1984). Consequently, these compounds are also released preferentially during the smoldering stages. Figure 1.2 shows the sequence of the emission of CO_2 (maximum in the

Table 1.4 Emission ratios for trace gases and aerosols from biomass burning, based on field and laboratory studies

Species	Field studies (range)[a]	Laboratory studies (range)[b]	Best guess[c]
Gases[d]			
CO	65–140	59–105	100
Methane	6.2–16	11–16	11
NMHC[e]	6.6–11.0	3.4–6.8	7
Nitrous oxide	0.18–2.2	0.01–0.05	0.1
NO_x	2–8	0.7–1.6	2.1
Ammonia	0.9–1.9	0.08–2.5	1.3
RCN[f]	–	0.24–0.93	0.6
SO_x[g]	0.1–0.34		0.3
Carbonyl sulfide	0.005–0.016		0.01
Methylchloride	0.023–0.033	0.02–0.3	0.05
Hydrogen	33		33
Ozone[d,h]	4.8–40		30
Aerosols[i]			
TPM[j]	12–82		30
POC[k]	7.9–54		20
EC[l]	2.2–16		5.4
Potassium	0.24–0.58		0.4

a. Based on data from Andreae et al. (1988a, 1990a); Cofer et al. (1988, 1989); Crutzen et al. (1979, 1985); DeAngelis et al. (1980); Delmas (1982); Greenberg et al. (1984); Hegg et al. (1987); Hegg et al. (1988); Khalil and Rasmussen (1984); Miner (1969); Ward (1986); Winstead et al. (1990).
   The range shown is a range of means from these studies, not a range of individual measurements.
b. Based on data from Crutzen et al. (1990) and Rasmussen et al. (1980). The range shown is from individual burns of different types of biomass (savanna grasses, pine straw).
c. Based on a more or less subjective evaluation of the information in columns 1 and 2.
d. Results are expressed as moles of substance X emitted per 1000 moles of CO_2 emitted.
e. Nonmethane hydrocarbons (C_2–C_{10}).
f. $(CN)_2$ + HCN + CH_3CN + C_2H_5CN + C_2H_4CN.
g. SO_2 + aerosol sulfate.
h. Photochemically produced ozone in the burning plumes.
i. All data in g/kg $C(CO_2)$.
j. Total particulate matter.
k. Particulate organic carbon (including elemental carbon).
l. Elemental (black-soot) carbon.

flaming stage), CO (maximum in the early smoldering stage), and the organic acids (maximum in the late smoldering stage) from an experimental fire (D. Scharffe, W. Hartmann, M. O. Andreae, unpublished data).

Nitrogen is present in plant biomass mostly as amino groups (R-NH_2) in the amino acids of the proteins. During combustion it is released by pyrolytic decomposition of the organic matter and then partially or completely oxidized to various volatile nitrogen compounds. NO is the single most abundant
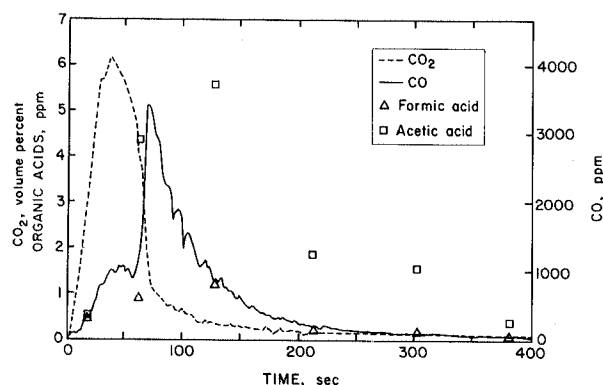
Figure 1.2 Concentrations of CO_2, CO, formic acid, and acetic acid in the smoke from an experimental biomass fire as a function of time. The flaming stage in this fire lasted for about 60 seconds. Concentrations are in volume percent for CO_2 and in volume mixing ratios (ppm) for the other species (1% = 10,000 ppm).

species emitted, but it represents only some 10% to 20% of the nitrogen initially contained in the fuel. Other nitrogen compounds (NO_2, N_2O, NH_3, HCN, organic nitriles and nitrates) account for another 10% to 20% of the fuel nitrogen, but some 60% to 70% of these compounds are released in as yet unknown forms, possibly as molecular nitrogen (Crutzen et al., 1990). Almost none of the fuel nitrogen is left in the ash. This is different for sulfur, about one-half of which remains in the ash (Delmas, 1982), probably due to the difference in the speciation of sulfur and nitrogen in plants. In contrast to nitrogen, which is almost exclusively present as amino groups in proteins, only part of the sulfur in plants is organically bound in the form of sulfur-containing amino acids in proteins (50% to 90%) (Turner and Lambert, 1980), and only this organic sulfur fraction is likely to be volatilized during combustion—mostly to SO_2 but to a small extent also to carbonyl sulfide (COS). The rest of the plant sulfur is in the form of sulfate and small amounts of sulfate esters that are pyrolyzed to sulfate during combustion. Sulfate is not volatile at the temperatures prevailing in biomass fires and is either retained in the ash or, to some extent, incorporated into smoke particles. The same applies to phosphorus, which is also present largely as phosphate esters that are broken down to nonvolatile phosphate during combustion. The ratio between the sum of identifiable nitrogen gas emissions and sulfur emissions (Table 1.4) is 14, very close to the N/S ratio in plant tissue, which is about 15 and quite constant from species to species (Thompson et al., 1970). This is

roughly consistent with the observations that about two-thirds of nitrogen is volatilized in still unidentified forms and that about one-half of the sulfur is left in the ash.

Table 1.5 combines the estimates of biomass burning rates in the tropical regions and worldwide (Tables 1.2 and 1.3) with a best estimate of the emission ratios (Table 1.4) to derive regional and global rates of pyrogenic emissions. The uncertainty of these estimates is about 50% in the case of CO_2, where the emission amount is relatively well constrained, and about a factor of 2 for most of the other gases, where additional uncertainty is contributed by the limited data base on emission ratios.

In spite of these uncertainties in the quantitative estimates, it is quite evident from this compilation that biomass burning results in globally important contributions to the atmospheric budget of several of these pollutant gases (Table 1.6). Since much of the burning is concentrated in relatively limited regions, such as the African savannas, and occurs over a limited time, it is not surprising that it results in levels of atmospheric pollution that rival and sometimes exceed those in the industrialized regions of the developed nations.

This applies especially to a group of gases that are the main ingredients of "classical" smog chemistry in the atmosphere—hydrocarbons, carbon monoxide, and nitrogen oxides (NO_x). As is discussed later, these species interact to form other pollutants, particularly ozone (O_3). About 20% to 30% of the global emissions of these compounds is attributable to biomass burning (Table 1.6). This budget ignores the natural emissions of the very short-lived terpenes and isoprene. Since only about half of the total source flux of these species is from anthropogenic emissions (the rest from natural sources), biomass burning accounts for roughly one-half of the anthropogenic sources of atmospheric hydrocarbons, CO, NO_x, and tropospheric ozone.

Methane (CH_4) and nitrous oxide (N_2O) contribute to the atmospheric greenhouse effect and are long-lived enough to enter the stratosphere and contribute to the ozone cycle there. Their pyrogenic emissions are on the order of about 10% of the global source flux. The emission ratios for both of these gases are uncertain, however, and it is quite possible that the pyrogenic fraction could be as high as 15% for methane. In the case of N_2O, on the other hand, recent evidence (Crutzen et al., 1990, Winstead et al., 1991) suggests that the emission ratios previously published may have been too high due to an experimental arti-

Table 1.5 Estimates of tropical and global emissions from biomass burning (Tg element/yr)

| Species | Emission ratio | Tropical regions of | | | | Tropics total | World total |
		America	Africa	Asia	Australia		
Carbon burned[a]		780	1450	980	200	3410	3940
Gases[b]							
CO_2[c]		690	1270	860	180	3000	3460
CO	100	70	130	90	20	300	350
Methane	11	8	14	10	2	33	38
NMHC[d]	7	5	9	6	1	21	24
Nitrous oxide	0.1	0.16	0.30	0.20	0.04	0.70	0.81
NO_x	2.1	1.7	3.1	2.1	0.4	7.4	8.5
Ammonia	1.3	1.0	1.9	1.3	0.3	4.6	5.3
RCN[e]	0.6	0.4	0.9	0.6	0.1	2.1	2.4
SO_x[f]	0.3	0.6	1.0	0.7	0.1	2.4	2.8
Carbonyl sulfide	0.01	0.02	0.03	0.02	<0.01	0.08	0.09
Methyl chloride	0.05	0.10	0.19	0.13	0.03	0.44	0.51
Hydrogen	33	4	7	5	1	16	19
Ozone[b,g]	30	80	150	100	20	360	420
Aerosols[h]							
TPM[i]	30	21	38	26	5	90	104
POC[j]	20	14	25	17	4	60	69
EC[k]	5.4	3.7	6.9	4.7	1.0	16	19
Potassium	0.4	0.9	1.7	1.1	0.2	3.9	4.5

Note: Based on the emission ratio estimates from Table 1.4 and the estimates of the regional and global rates of biomass burning from Tables 1.2 and 1.3. All emission ratios are given in Tg element per year—e.g., in Tg $N(NO_x)$ or $S(SO_x)$ per year. The uncertainty of these estimates is about ±50% in the case of CO_2, about a factor of 2 for the other species.
a. From Tables 1.2 and 1.3.
b. Emission ratio expressed as moles of substance X emitted per 1000 moles of CO_2 emitted.
c. These values represent the actual amount of CO_2 emitted from the fires. They are 88% of the amount of carbon burned, since about 12% is emitted as CO, methane, and NMHC. These compounds will be eventually converted to CO_2 by photochemical oxidation in the atmosphere, however.
d. Nonmethane hydrocarbons (C_2–C_{10}).
e. $(CN)_2$ + HCN + CH_3CN + C_2H_5CN + C_2H_4CN.
f. SO_2 + aerosol sulfate.
g. Photochemically produced ozone in the burning plumes.
h. Emission ratio in g/kg $C(CO_2)$.
i. Total particulate matter (emission rate in Tg/yr).
j. Particulate organic carbon (including elemental carbon).
k. Elemental (black-soot) carbon.

fact. Biomass burning may thus play only an insignificant role in the global budget of this species. Additional information on both the pyrogenic and the other sources of N_2O is needed before the budget of this species can be assessed with a reasonable amount of accuracy (Andreae and Schimel, 1989).

The global atmospheric budget of ammonia (NH_3) is not well known. Based on the discussion in Andreae et al. (1989) we estimate global emissions to be in the range of 20 to 80 Tg N/yr, with a best-guess estimate of 44 Tg N/yr. Microbial release from animal excreta and soils makes up the largest fraction of these emissions, while biomass burning contributes only some 12%.

In contrast to the nitrogen species, where py-

rogenic emissions are very important, only relatively small amounts of sulfur dioxide and aerosol sulfate are emitted. Biomass burning contributes only about 1.3% to the total atmospheric sulfur budget and represents about 3% of the anthropogenic emissions (Andreae, 1991). Still, since most of the natural emissions are from the oceans and most of the anthropogenic emissions are concentrated in the industrialized regions of the temperate latitudes, biomass burning does make a pronounced impact on the sulfur budget over remote continental regions, such as the Amazon and Congo basins (Andreae et al., 1988a; Andreae and Andreae, 1988; Bingemer et al., 1990). Here, sulfur

Table 1.6 Comparison of global emissions from biomass burning with emissions from all sources (including biomass burning)

Species	Biomass burning (Tg element/yr)	All sources (Tg element/yr)	Biomass burning (percent)	Reference for "all sources" estimate
CO_2 (gross from combustion)	3500	8700[a]	40	Bolin et al. (1986)
CO_2 (net from deforestation)	1800	7000[b]	26	Bolin et al. (1986)
CO	350	1100	32	WMO (1985)
Methane	38	380	10	Cicerone and Oremland (1988)
NMHC[c]	24	100	24	Ehhalt et al. (1986)
Nitrous oxide	0.8	13	6	Bolle et al. (1986)
NO_x	8.5	40	21	Logan (1983)
Ammonia	5.3	44	12	Andreae et al. (1989)
Sulfur gases	2.8	150	2	Andreae (1990)
Carbonyl sulfide	0.09	1.4	6	Khalil and Rasmussen (1984)
Methyl chloride	0.51	2.3	22	WMO (1985)
Hydrogen	19	75	25	Conrad and Seiler (1986)
Ozone	420	1100	38	Crutzen (1988)
TPM[d]	104	1530	7	Peterson and Junge (1971)
POC[e]	69	180	39	Duce (1978)
EC[f]	19	<22	>86	Turco et al. (1983)

a. Biomass burning plus fossil fuel burning.
b. Deforestation plus fossil fuel burning.
c. Nonmethane hydrocarbons (excluding isoprene and terpenes).
d. Total particulate matter (Tg/yr).
e. Particulate organic carbon (including elemental carbon).
f. Elemental (black-soot) carbon.

fluxes to the vegetation may be enhanced by as much as a factor of five due to tropical biomass burning.

Methyl chloride, CH_3Cl, is also released by biomass burning and has actually been proposed as a tracer for pyrogenic emissions (Rasmussen et al., 1980). This gas is of great significance for the stratospheric ozone budget; it is the second-largest source of stratospheric chlorine. The pyrogenic source corresponds to about 0.5 Tg Cl/yr (0.7 Tg CH_3Cl/yr), which is about 22% of the global emissions.

Emission of Aerosol Particles (Smoke)

Even though the smoke from biomass fires is one of the most obvious emissions, often visible in the tropics as a continuous pall hanging in the air for days or weeks, quantitative estimates on the amounts of particulate matter released are still highly uncertain. In Table 1.5 the emission of total particulate matter (TPM) is estimated as 104 Tg/yr, most of which is organic matter. Of the particulate organic carbon (POC) released (70 Tg/yr), about one-quarter (20 Tg/yr) is in the form of black, elemental (soot) carbon (EC). Based on these estimates, POC from biomass burning accounts for over one-third of the organic

carbon aerosol released globally (Duce, 1978). These estimates, however, are much lower than those of Seiler and Crutzen (1980), who suggested an emission rate of 200 to 450 Tg/yr for TPM, of which about 90% is assumed to be carbon compounds, and 90 to 180 Tg/yr for elemental carbon.

This discrepancy results from the large difference in the emission ratios used: Seiler and Crutzen's estimate is based on early work by Ward (personal communication to Seiler and Crutzen, 1979), who had suggested emission ratios of 24 to 180 g TPM/kg $C(CO_2)$. The value of 30 g TPM/kg $C(CO_2)$ is based on our work in Amazonia (Andreae et al., 1988a), the work by Ward (1986), and the data of Radke et al. (1988). In Amazonia, we sampled plumes that were quite "old" and had traveled for about one day following the burn and obtained apparent emission ratios of 6 to 25 g/kg $C(CO_2)$. Due to the delay between emission and sampling in our work, it is likely that a substantial amount of the aerosol in particles larger than a few micrometers in diameter had already fallen out. The emission measurements of Ward (1986) and Radke et al. (1988), on the other hand, were conducted in the immediate vicinity of the fires and were

therefore not influenced by significant amounts of fallout. Ward reports TPM emission ratios in the range from 2 to 46 g/kg $C(CO_2)$, with average values of 22 and 37 g/kg $C(CO_2)$ for flaming and smoldering conditions, respectively. Based on 71 measurements from 10 different fires, Radke et al. (1988) derive a mean emission ratio of 44 ± 31 g/kg $C(CO_2)$ for aerosol particles of less than 2 μm diameter. As some of the particles sampled very closely above the fire are large enough to fall out almost immediately, it appears that a value of 30 g/kg $C(CO_2)$ is a reasonable estimate for the emission of particulate matter that may become subject to atmospheric transport.

Our measurements in Amazonia showed that the carbon content of this aerosol is about 66%, which is consistent with the aerosol particles consisting mostly of partially oxygenated organic matter. The content of black elemental carbon in smoke particles from biomass burning is highly variable. In smoldering fires it is as low as 4% (weight percent carbon in TPM), while in intensively flaming fires it can reach 40% (Ward, 1986; Patterson and McMahon, 1984; Cachier et al., 1989). We are using a value of 18%, based on our work in Amazonia (Andreae et al., 1988a). From this and the estimate for global TPM emissions in Table 1.5 (104 Tg/yr), we obtain a source estimate for black carbon aerosol of 19 Tg/yr. This accounts for a very large fraction of the global emissions, which have been estimated to fall into the range of 3 to 22 Tg/yr (Turco et al., 1983).

Charcoal Formation and Carbon Storage

In their 1980 paper, Seiler and Crutzen drew attention to an unexpected consequence of biomass burning: They argued that the formation of charcoal during burning would lead to the long-term sequestering of carbon in soils and sediments and therefore provide a sink for atmospheric carbon. In the absence of burning, photosynthesis and respiration in terrestrial ecosystems form a closed cycle in which just as much CO_2 is released to the atmosphere during the biochemical oxidation of the plant matter as was taken up during its production by photosynthesis. Thus, there is no net flux of CO_2 to or from the atmosphere. During combustion, however, some of the plant matter is turned into charcoal, which may either remain on the ground after the burn or be transported away in the smoke. Once formed, charcoal and soot carbon do not appear to be reoxidized back to CO_2, even over geological time scales. This process therefore provides a long-term sink for atmospheric CO_2 and, inci-

dentally, a net source of oxygen to the atmosphere. While this mechanism appears very plausible on a qualitative basis, its quantitative importance remains controversial.

The amount of charcoal and soot that becomes airborne during biomass fires can be estimated using the data on the elemental carbon component of the smoke aerosol given in Tables 1.4 and 1.5. The emission ratio estimate of 3.7×10^{-3} corresponds to about 1.4 g C per kg of burned biomass. Since only a fraction of the above-ground biomass is burned (20% to 80%, depending on vegetation type), the final fraction of biomass that becomes airborne as charcoal or soot particles is very small, probably less than 0.1%. This is consistent with the results of a study on the cycle of charcoal from biomass burning by Suman (1984, 1988), who estimated that only 5% of the charcoal produced in a coastal watershed reached sediments in the adjacent Gulf of Panama. Most of this charcoal is transported by rivers; only about 3% is carried by wind.

The main mechanism for charcoal storage must therefore be its incorporation into terrestrial soils and sediments. Seiler and Crutzen (1980) present a review of the literature and show that charcoal layers do indeed occur frequently in tropical and temperate soils. They estimate that 20% to 30% of the carbon present on the ground after a biomass fire is in the form of charcoal. At the burning efficiency of 25% assumed by Seiler and Crutzen, this would correspond to conversion of 15% to 22% of the preburn biomass into charcoal. Fearnside et al. (1990) measured the amount of charcoal produced in clearing fires in Amazonia and found a much lower rate of charcoal production—only about 3.6% of preburn above-ground carbon, which is about 20% of the value estimated by Seiler and Crutzen. As a result of these uncertainties, the range of estimates for the global rate of charcoal formation and the resulting sequestering of CO_2 is rather large—about 200 to 1700 Tg C/yr. If the actual value falls near the high end of this range, it could imply that as much as 20% of the approximately 7000 Tg C added per year to the world atmosphere may be removed by charcoal formation.

Outstanding Uncertainties

One of the most intriguing aspects concerning emissions from biomass burning is the fate of fuel nitrogen. It is well established from both field and laboratory studies that most of the nitrogen contained

in the biomass fuel is volatilized. However, only some 30% to 40% of the nitrogen released is in the form of chemical species (such as NO, NO_2, NH_3, and HCN) which are readily deposited and recycled into plant nutrients. Most of the remainder appears to be molecular nitrogen (Lobert et al., 1990), and therefore biomass burning may cause a substantial loss of nitrogen from tropical ecosystems.

The pyrogenic emission rate of N_2O, a trace gas whose atmospheric budget is very inadequately understood, also needs to be better defined. This is especially important since N_2O is a contributor to the greenhouse effect and a precursor of stratospheric NO_x, which in turn is important in regulating stratospheric ozone.

Another important issue is the production rate of charcoal during biomass combustion. Given the wide range of estimates, this process may be either a trivial sink of atmospheric CO_2 or large enough to almost compensate for the amount of CO_2 released due to deforestation.

Finally, much uncertainty persists regarding the rate of particulate emissions from biomass burning. Since aerosols can be observed and measured from satellites, they provide a potentially useful tool for the estimation of global rates of pyrogenic emission. It is therefore essential to have accurate data on the emission ratios and optical characteristics of smoke aerosols from biomass burning.

Transport and Photochemistry in the Smoke Plumes

Long-Range Transport of Smoke Plumes
The hot gases from the fires rise buoyantly in the atmosphere, entraining ambient air. Often, a cloud begins to form on the smoke plume. If this cloud produces rain, some particulate matter and soluble gases may already be scavenged and removed at this stage. In most cases, however, the clouds will dissolve again without rainfall, and the plume will start to drift horizontally with the prevailing winds. The height to which the smoke plumes can rise is limited in the tropics by the trade-wind inversion, which is present at an altitude of some 3 to 5 km. When the rising smoke plumes have become trapped at an inversion layer and start spreading horizontally, they will tend to become stretched out into relatively thin layers of great horizontal extent. Such thin haze layers can now travel very far from their point of origin without losing their identity. An example of one such layer, as ob-

served by Lidar in the middle of the Amazon Basin, some 1000 km from its source, is shown in Figure 1.3.

The further fate of the smoke-laden air masses depends on the large-scale circulation of the continent from which they originate. In tropical Africa, the plumes will usually travel in a westerly direction and toward the equator. As they approach the Intertropical Convergence Zone (ITCZ), vertical convection in the troposphere intensifies, destroys the layered structure, and results in the distribution of the pyrogenic emissions throughout the lower troposphere. Finally, in the ITCZ region, smoke and gases from biomass burning may be injected into the middle and upper troposphere, maybe even into the stratosphere. Air masses from the biomass burning regions in South America are usually moving toward the south and southeast, due to the effect of the Andes barrier on the large-scale circulation. Here, again, they may become entrained into a convergence zone, the seasonal South Atlantic Convergence Zone (SACZ). This convergence zone becomes established in austral spring, when biomass burning is abundant. The CO measurements from the Measurement of Air Pollution from Satellites (MAPS) satellite instrument tended to show a tendency for CO buildup in the middle to upper troposphere in the regions near the ITCZ and the SACZ (Reichle et al., 1986; H. G. Reichle, personal communication, 1989).
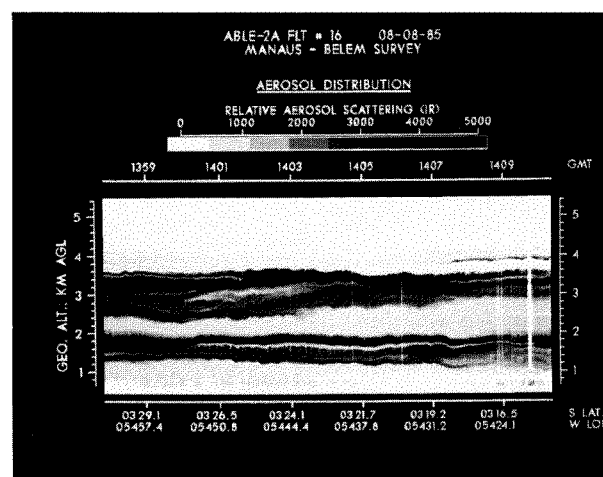

Figure 1.3 Vertical profile of haze layers from biomass burning as seen by Lidar over the central Amazon Basin. The vertical scale indicates the height above ground level; the horizontal scales, flight time (top) and geographical coordinates (bottom). Aerosol concentration based on infrared (IR) light scattering is indicated by a grey scale from low (white) to high (black). (Source: E. V. Browell, NASA/LARC)

Evidence for the efficiency of these transport mechanisms is abundant. The smoke plumes from the fires in South America and Africa are easily seen from space and have been the subject of investigations from the Space Shuttle. They have been mapped using various space-borne sensors, in particular the Advanced Very High Resolution Radiometer (AVHRR) instruments on the National Oceanic and Atmospheric Administration (NOAA) series satellites (Figure 1.1; Kaufman et al., 1990; Setzer and Pereira, 1990). At the ground, haze and smoke from fires some thousand kilometers away are still so dense that airports in the middle of the Amazon Basin are frequently closed during the burning season.

Less obvious than the visible smoke, but even more indicative of the large extent to which the emissions from burning are transported around the globe, are the results of chemical measurements from satellites, aircraft, and research vessels. Soot carbon and other pyrogenic aerosol constituents have been measured during research cruises over the remote Atlantic and Pacific (Andreae, 1983; Andreae et al., 1984). Ozone maxima in the ITCZ region over the Atlantic Ocean may be attributed to the presence of biomass burning plumes (Winkler, 1988). Carbon monoxide and ozone originating from fires in Africa were consistently observed during the NASA/CITE-3 research flights off the coast of Brazil (Andreae et al., 1990a). On an even larger scale, high levels of ozone and CO are seen from satellites over the tropical regions of Africa and South America, and large areas of the surrounding oceans (Fishman and Larsen, 1987; Reichle et al., 1986).

Smog Chemistry in the Smoke Plumes

The gases emitted in the biomass fires contain essentially the same constituents as the mixture which forms the starting material for urban smog: carbon monoxide, hydrocarbons, and nitrogen oxides. Once such a mixture is exposed to sunlight, the same chemical reactions take place, whatever its origin: Hydrocarbons are oxidized photochemically first to various peroxides, aldehydes, etc., then to CO. This CO is added to the amount directly emitted from the fires and is finally oxidized to CO_2. In the presence of elevated levels of NO_x, as will be the case in the smoke plumes, the oxidation of CO and hydrocarbons is accompanied by the formation of ozone (Crutzen, 1987). The efficiency of ozone formation— that is, the amount of ozone formed per molecule of hydrocarbon oxidized—depends on the proportions of hydrocarbons, NO_x, and O_3 present in the reaction

mixture and thus on the history of transport and mixing of the air mass involved (Chatfield and Delany, 1990).

Environmental Impacts

Ozone Pollution of the Troposphere

In view of the large amounts of hydrocarbons and NO_x emitted from biomass fires, it is not surprising that very high concentrations of ozone are produced in the plumes, often exceeding values typical of industrialized regions (Crutzen et al., 1985; Delany et al., 1985; Kirchhoff and Nobre, 1986; Logan and Kirchhoff, 1986; Cros et al., 1987, 1988; Andreae et al., 1988a, 1990a, 1991). The highest concentrations, typically in the range from 50 to 100 ppb, are usually found in discrete layers at altitudes from 1 to 5 km (Figure 1.4). Usually, the concentrations at ground level are substantially lower. They typically show a pronounced daily cycle, with a minimum at night and a maximum near midday. This cycle is controlled by the balance of O_3 sources and sinks: At night O_3 consumption by deposition to vegetation and by the reaction with NO emitted from soils reduces the concentration of ozone near the earth's surface; during the day, it is replenished by photochemical ozone
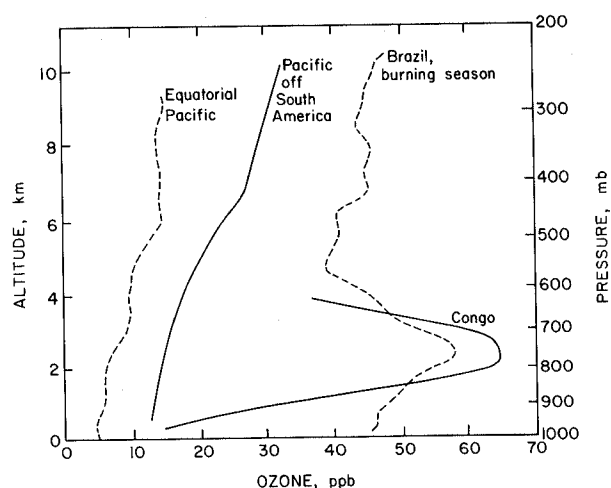

Figure 1.4 Vertical profiles of ozone in the tropical troposphere. The profile over the equatorial Pacific shows no influence from biomass burning (Fishman et al., 1987), while the profile over the Pacific off South America (Seiler and Fishman, 1981) suggests ozone enhancement due to long-range transport from the tropical continents. The ozone profiles over Brazil (Crutzen et al., 1985) and the Congo (Andreae et al., 1989a) show high ozone concentrations between 1 and 4 km altitude due to photochemical production in biomass burning plumes (figure modified from Fishman, 1988).

formation and downward mixing of ozone-rich air from higher altitudes. Over an unpolluted tropical rainforest, such as in the central Amazon Basin during the wet season, O_3 levels are very low—below 10 ppb at midday, and below 3 ppb at night (Gregory et al., 1990; Kirchhoff et al., 1990). Under somewhat more polluted conditions, e.g., in central Amazonia during the dry season, nighttime values are still very low, but daytime O_3 concentrations reach 10 to 30 ppb at the level of the tree crowns. Finally, in tropical Africa, where biomass burning currently has the strongest impact, surface ozone concentrations in excess of 40 ppb are frequently measured, especially during the dry season (Cros et al., 1988). These values are similar to those observed in the highly polluted regions of the eastern United States and of Central Europe (Logan, 1985, and references therein). Studies in temperate forest regions have linked such levels of ozone pollution to the damage to trees and vegetation that has become widespread in Europe and North America. In view of the sharp increase of O_3 with altitude frequently observed in the tropics, the likelihood of vegetation damage by ozone is especially high in mountainous regions, where the ground surface intersects the levels at which ozone concentrations above 70 ppb are encountered. Ozone episodes with ground-level concentrations of 80 to 120 ppb must be expected to occur in the tropics, particularly during the dry season, when photochemically reactive air becomes trapped under a subsiding inversion layer.

The increase of tropospheric ozone concentrations is a cause for concern even beyond the likelihood of plant damage by this gas: Ozone is also an efficient absorber of infrared radiation and thus acts as a "greenhouse gas" in the same way as CO_2. In fact, the global increase in tropospheric O_3 concentrations contributes about 15% to the overall greenhouse warming (Ramanathan et al., 1985). The increase of O_3 over the tropics contributes strongly to this effect: Photochemical ozone production from pyrogenic emissions accounts for about one-third of the total input of ozone into the troposphere (Table 1.6), about the same amount as produced from fossil fuel emissions in the industrialized regions of the Northern Hemisphere (the rest is due to stratospheric inputs). The ozone soundings from Natal (Kirchhoff and Nobre, 1986) and from the Brazilian savanna region (Delany et al., 1985) show that the effect of ozone production from biomass burning is quite pronounced even in the middle and upper troposphere, where it contributes most significantly to greenhouse

warming. Consequently, biomass burning may be responsible for up to one-half of the greenhouse warming due to increasing tropospheric ozone (Figure 1.5).

Perturbation of Oxidant Cycles in the Troposphere

The large-scale change of tropospheric ozone levels that is being observed in the tropics and is expected to increase in the future is an indication of a fundamental change in the way the troposphere behaves chemically. Many gases, particularly hydrocarbons, are continuously emitted into the atmosphere from natural and anthropogenic sources. A buildup of these gases in the atmosphere is prevented by a self-cleaning mechanism, whereby these substances are slowly "combusted" photochemically to CO_2. The key molecule responsible for this oxidation process is the hydroxyl radical (OH). The reaction chains involved are such that ozone and OH are consumed when the concentration of NO_x is low. This is the "normal" condition of the unpolluted troposphere. Based on the observed increase of methane and CO in the atmosphere, Crutzen (1987) suggested the possibility of a global decrease in OH and O_3, leading through a feedback mechanism to a further increase in CH_4 and
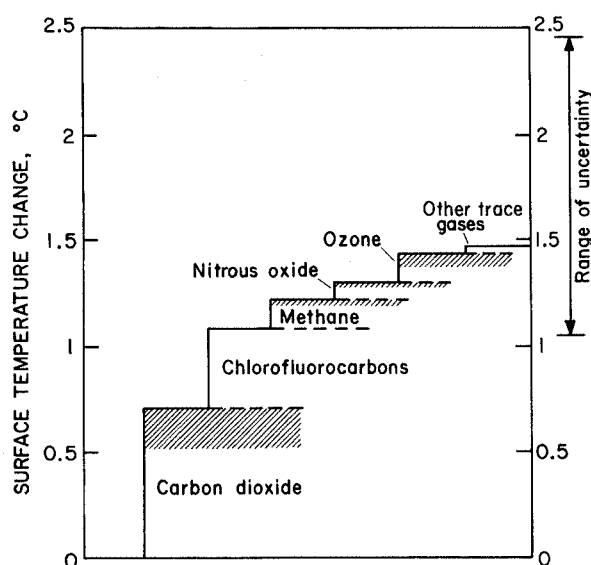

Figure 1.5 Cumulative equilibrium surface temperature warming ("greenhouse effect") due to increasing trace gas concentrations from A.D. 1980 to 2030 as computed by a one-dimensional climate model (after Ramanathan et al., 1985). Shaded areas indicate the effect attributable to deforestation and biomass burning. Due to climate feedback mechanisms the expected changes in global temperatures are 0.8 to 2.6 times the values given in this figure.

CO, and a possibly unstable condition of the atmosphere. Injection of large amounts of NO_x from biomass burning may reverse this process, since hydrocarbon oxidation in the presence of elevated amounts of NO_x *produces* additional amounts of O_3 and OH. The model calculations of Keller et al. (1991) predict a tenfold increase in regional OH concentrations to result from deforestation and biomass burning in the tropics. The consequences of driving a large fraction of the world atmosphere from its "natural" O_3-consuming mode of operation into the opposing, O_3-producing one are unforeseeable at this time.

Climate Change

We have already discussed the fact that the clearing of the tropical rainforests is responsible for about 25% of the greenhouse warming due to increasing CO_2 and that increasing tropospheric ozone as well adds to the greenhouse effect. But biomass burning also releases other gases that contribute to greenhouse warming, particularly methane and nitrous oxide. In the case of the latter two gases, biomass burning accounts for only about 10% of the global sources, but probably for a much greater fraction of the *increase* in global emissions, since many of the other sources, such as natural wetlands, are constant or actually shrinking. Based on the estimates of the temporal trends of methane source strengths from 1940 to 1980 given by Bolle et al. (1986), the pyrogenic contribution to the increase in methane emissions over that time period is 21%. The current uncertainty about the atmospheric mass balance of N_2O makes it very difficult to estimate the contribution of biomass burning to its increasing tropospheric concentration: It may be as high as 30%. The fraction of greenhouse warming attributable to biomass burning and deforestation is indicated as shaded areas in Figure 1.5.

The climatic effect of the smoke aerosols is beyond current understanding due to the complex nature of the interactions involved. Because of the limited lifetime of aerosol particles (on the order of days) compared to the lifetime of most of the "greenhouse gases," their climatic effects act initially more on a regional than a global scale. Since the equatorial regions, particularly the Amazon Basin, the Congo Basin, and the area around Borneo, are extremely important in receiving solar energy and in redistributing this heat vertically through the atmosphere, any change affecting the operation of these "heat engines of the atmosphere" must be viewed with great concern. Aerosols can influence climate directly through

changing the earth's radiation balance. They can reflect sunlight back into space and thus reduce the amount of heat the earth receives. Black-soot aerosol, on the other hand, may absorb sunlight and result in heating of the atmosphere. There appears to be a weak consensus by climatologists that these direct effects are not large at this time relative to other agents of climate change. A greater source of concern is the influence of pyrogenic particles on the behavior of clouds. Cloud droplets form on aerosol particles, called cloud condensation nuclei (CCN). The properties of the cloud depend on the number of available CCN: The more CCN, the more droplets form, which results in a smaller droplet size, given a constant amount of available water. Clouds made up of smaller droplets are whiter and reflect more sunlight back into space but are less likely to produce rain. Since clouds are one of the most important controls on the heat balance of the earth, any large-scale modification of cloud properties is likely to have a strong impact on global climate. The limited body of data that is available to date on the production of CCN by biomass fires suggests strongly that pyrogenic aerosol particles are very effective as CCN and that large numbers of such particles are released during burning (Eagen et al., 1974; Desalmand et al., 1982; Desalmand, 1987; Hallett et al., 1989; Rogers et al., 1990). Aging for up to 20 hours increased the percentage of aerosol particles that were effective as CCN to almost 100% (Hallett et al., 1989).

The potential changes in precipitation efficiency caused by increased abundance of CCN add to the perturbation of the hydrological cycle in the tropics caused by changes in the characteristics of the land surface brought about by deforestation and desertification. Tropical forests are extremely efficient in returning water that has fallen on them as rain back to the atmosphere in the form of water vapor. There it can form clouds and rain again, and the cycle can repeat itself many times. A region like the Amazon Basin can thus retain water (which ultimately comes from the ocean and will return there) for a long time and maintain a large "standing stock" of water. If the forest is replaced by grassland or, as often is the case, converted into an essentially unvegetated surface by erosion and loss of topsoil, water runs off quickly and returns through streams and rivers to the ocean without much chance of recycling. Beyond the unfavorable consequences that such large-scale changes of the availability of water will have on human activities, this modification of the hydrological cycle may itself perturb climate. The atmosphere makes use of the

potential for storing energy in the form of water vapor and releasing this energy again when the vapor condenses into cloud droplets as an important mechanism for the redistribution of heat. If less water is available for this purpose, the heat absorbed at the ground has to be moved away by radiation and dry convection, leading to higher surface temperatures and a change in the vertical distribution of heat. Such perturbations of the heat and water balance of the atmosphere must be viewed with great concern.

Acid Deposition

After acid rain became a notorious environmental problem in Europe and North America, scientists were somewhat surprised to learn that it was widespread in the tropics as well (Table 1.7): Acid rain was reported from Venezuela (Steinhardt and Fassbender, 1979; Galloway et al., 1982; Sanhueza et al., 1989), from Brazil (Andreae et al., 1988b), from Africa (Lacaux et al., 1987, 1988; J. Lacaux, personal communication, 1989), and from Australia (Ayers and Gillett, 1988). In all instances, organic acids (especially formic and acetic acids) and nitric acid were shown to account for a large part of the acidity, in contrast to the situation in the industrialized temperate regions, where sulfuric acid and nitric acid

predominate. It was originally thought that the organic acids were largely derived from natural, biogenic emissions, probably from plants (Talbot et al., 1988; Andreae et al., 1988b; Keene et al., 1986). However, more recent evidence shows that they may be derived to a large extent from direct emission of acetic acid from biomass burning and to the photochemical formation of formic and acetic acid in the plumes (Helas et al., 1991). In regions affected by biomass burning, pyrogenic NO_x emissions overwhelm by far the natural sources of NO_x, e.g., soil emissions and NO formation in lightning bolts. Nitric acid is formed photochemically from the NO_x emitted in the fires. A modeling study simulating the effects of biomass burning and a moderate amount of additional pollution, mostly connected with the activities related to logging, etc., suggests that pH values of about 4.2 can be expected in the tropics due to the formation of nitric acid alone (Keller et al., 1991). The addition of organic acids to precipitation can be expected to drive pH down to values well below 4. Such values have indeed been frequently observed in Africa (J. Lacaux, personal communication, 1989). For comparison, the mean pH measured during the period 1963 to 1982 at the Hubbard Brook site in New Hampshire, a classical site for the study of acid rain,

Table 1.7   Rainwater pH and acid deposition at some continental tropical sites and in the eastern United States

	pH		Rainfall (cm)	Deposition (kg H^+/ha/yr)	Reference
	Mean[a]	Range			
Venezuela					
San Eusebio	4.6	3.8–6.2	158	0.39	Steinhardt and Fassbender (1979)
San Carlos	4.8	4.4–5.2	—	—	Galloway et al. (1982)
La Paragua	4.7	4.0–5.0	—	—	Sanhueza et al. (1989)
Brazil					
Manaus, dry season	4.6	3.8–5.0 }	240[b]	0.29[b]	Andreae et al. (1990b)
Manaus, wet season	5.2	4.3–6.1 }			
Australia					
Groote Eylandt	4.3		—	—	Langkamp and Dalling (1983)
Katherine	4.8	4.2–5.4	—	—	Galloway et al. (1982)
Jabiru	4.3		—	—	Ayers and Gillett (1988)
Ivory Coast					
Ayame	4.6	4.0–6.5	179	0.41	Lacaux et al. (1987)
Congo					
Boyele	4.4		185	0.74	Lacaux et al. (1988)
Eastern USA	4.3	3.0–5.9	130	0.67	Barrie and Hales (1984)

a. Volume weighted.
b. Annual average.

was 4.2 (Likens et al., 1984), and the mean pH in rain sampled throughout the eastern United States in 1980 was 4.3 (Table 1.7; Barrie and Hales, 1984).

Acidic substances in the atmosphere can be deposited to plants and soils either by rain and fog (wet deposition) or by the direct removal of aerosols and gases at the surface (dry deposition). In the humid tropics, wet deposition accounts for most of the deposition flux, whereas in the savanna regions, especially during the dry season, dry deposition dominates. Acid deposition has been linked to forest damage in Europe and the eastern United States. It is thought that such damage is usually caused by a combination of factors, including acid deposition, ozone damage, and the concurrent exposure to other sources of stress, such as drought or insect infestation (Bormann, 1985). Acid deposition can act on an ecosystem by two major pathways: direct damage through the deposition of acidic aerosols and gases on leaves, or soil acidification. The danger of leaf injury is serious only at pH levels below 3.5, which is rarely encountered in the tropics (McDowell, 1988). However, in view of the presence of the highly soluble gaseous nitric and organic acids from biomass burning, it is quite likely that fog and dew can reach such pH levels during the dry season in many regions. Tropical forests may be inherently more sensitive to foliar damage than temperate forests due to the longer average leaf life in the tropics, where the leaves of many trees are shed only after two or more years. The resulting longer exposure of individual leaves may make cumulative damage more pronounced (McDowell, 1988).

Many tropical soils are likely to be relatively resistant to rapid acidification due to their high sulfate adsorption capacity (McDowell, 1988). However, there are also large areas where soils are quite susceptible to acidification, such as in Venezuela (Sanhueza et al., 1988). Furthermore, even in relatively resistant soils, chronic exposure to acid deposition will eventually lead to soil acidification and associated problems, like leaching of aluminum, manganese, and other cations. Microbial processes in the soils are also at risk of being perturbed. Nitrogen cycling is likely to be influenced, both by decreasing pH and by the addition of nitrate and ammonium ions from wet and dry deposition.

Many species of tropical animals have stages in their life cycles where they live in rainwater collected in bromeliads or similar plants. Other species, like frogs and salamanders, depend on water collected between dead leaves, mosses, etc., to keep their skin moist. Acid deposition poses a serious risk to these animals, which are essential components of the forest ecosystem. This applies particularly to the insects, which are essential to many rainforest species for pollination (Baker et al., 1983).

Disruption of Nutrient Cycles and Soil Degradation

Tropical ecosystems, both natural and agricultural, are frequently deficient in nitrogen or sulfur or both (Sanchez, 1976). When an area is burned, a substantial part of the nitrogen and sulfur present in the ecosystem is volatilized. As long as these elements are deposited again relatively nearby, this would imply no net gain or loss. However, in the case of nitrogen, only some 40% of the fuel nitrogen can be accounted for in the emissions. If the remainder is indeed emitted as molecular nitrogen, a significant overall loss of nutrient nitrogen results. This possibility needs to be investigated further. The interactions between fire and grazing in grasslands add a further complication (Hobbs et al., 1991). The nitrogen loss due to burning is much greater from ungrazed than from grazed areas, since the latter have less above-ground biomass exposed to fire. This effect is large enough that grazing may control whether a burned grassland gains or loses nitrogen.

On the other hand, ecosystems that are not burned, such as remaining areas of intact rainforest, will receive an increased nutrient input. Studies of rainwater chemistry in the central Amazon Basin suggest that as much as 90% of the sulfur and nitrogen deposited there is from sources outside the forest ecosystem, with long-range transport of emissions from biomass burning playing a major role (Andreae et al., 1990b). The effects of such increasing inputs of nutrients to the rainforests are not known. It must be remembered, however, that the increased nutrient inputs are accompanied by an increase in acid deposition and ozone concentration. The complex effect of environmental perturbations on tropical forest ecosystems will be difficult to analyze.

Besides the immediate volatilization of nitrogen during the burns, long-term changes in the microbial cycling of nitrogen in the soils appear to result from the use of burning as a tool of agriculture (Anderson et al., 1988; Levine et al., 1988). NO and N_2O emissions from soils at experimental sites that were burned were about twice as high as from soils at unburned sites. This effect persisted for at least six months following the burn. Other studies have also shown enhanced fluxes of nitrogen oxides from soils follow-

ing clearing of forest and conversion to grazing land (Matson et al., 1988), but in these studies the effect of burning was not isolated explicitly. Levine et al. (1990) found an increase in biogenic CH_4 and NO emissions from wetlands following vegetation burn-off. It is clear that much research still needs to be done in order to elucidate the effects of biomass burning on nutrient cycling and especially on nitrogen volatilization. The few studies available already do suggest, however, that deforestation and biomass burning contribute to the inputs of nitrogen oxides and the resulting perturbations of air quality and climate well beyond the direct emissions from the fires.

Perturbation of Stratospheric Chemistry and the Ozone Layer

Many of the trace gases released by biomass burning are involved in the chemical reaction cycles that control the stratospheric ozone layer. Methyl chloride, about 20% of which comes now from biomass burning, is the second-largest source of stratospheric chlorine. N_2O, for which biomass burning is also a possibly significant source, is long-lived enough to diffuse into the stratosphere, where it is broken down to reactive nitrogen species. Methane and hydrogen gas are oxidized in the stratosphere, forming CO_2 and H_2O. The fact that some biomass burning occurs in close vicinity to the Intertropical Convergence Zone is particularly relevant: In this region of intensive vertical convection, even relatively short-lived gases like nonmethane hydrocarbons may be injected into the stratosphere. COS is the only sulfur gas which is able to escape tropospheric oxidation and diffuse to the stratosphere. Here it is oxidized to form sulfuric acid aerosol particles, which scatter sunlight, and participate in the reaction cycles which control the abundance of stratospheric ozone (Oppenheimer, 1987). It is impossible at this time to predict what the overall effect of biomass burning on the fluxes of all of these species into the stratosphere and on the chemical reactions there will be. However, the potential for significant disruption of stratospheric chemical cycles is considerable enough to warrant further investigation by modeling and experiment.

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