Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles

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Biomass burning is widespread, especially in the tropics. It serves to clear land for shifting cultivation, to convert forests to agricultural and pastoral lands, and to remove dry vegetation in order to promote agricultural productivity and the growth of higher yield grasses. Furthermore, much agricultural waste and fuel wood is being combusted, particularly in developing countries. Biomass containing 2 to 5 petagrams of carbon is burned annually (1 petagram = 10^{15} grams), producing large amounts of trace gases and aerosol particles that play important roles in atmospheric chemistry and climate. Emissions of carbon monoxide and methane by biomass burning affect the oxidation efficiency of the atmosphere by reacting with hydroxyl radicals, and emissions of nitric oxide and hydrocarbons lead to high ozone concentrations in the tropics during the dry season. Large quantities of smoke particles are produced as well, and these can serve as cloud condensation nuclei. These particles may thus substantially influence cloud microphysical and optical properties, an effect that could have repercussions for the radiation budget and the hydrological cycle in the tropics. Widespread burning may also disturb biogeochemical cycles, especially that of nitrogen. About 50 percent of the nitrogen in the biomass fuel can be released as molecular nitrogen. This pyrodenitrification process causes a sizable loss of fixed nitrogen in tropical ecosystems, in the range of 10 to 20 teragrams per year (1 teragram = 10^{12} grams).

THE USE OF FIRE AS A TOOL TO manipulate the environment has been instrumental in the human conquest of Earth, the first evidence of the use of fires by early hominids dating back to 1 million to 1.5 million years ago (*1*). Even today, most human-ignited vegetation fires take place on the African continent, and its widespread, frequently burned savannas bear ample witness to this. Although natural fires can occur even in tropical forest regions (*2, 3*), the extent of fires has greatly expanded on all continents with the arrival of *Homo sapiens*. Measurements of charcoal in dated sediment cores have shown clear correlations between the rate of burning and human settlement (*4*). Pollen records show a shift with human settlement from pyrophobic vegetation to pyrotolerant and pyrophilic species, testimony to the large ecological impact of human-induced fires.

Natural fires have occurred since the evolution of land plants some 350 million to 400 million years ago and must have exerted ecological influences (*5*). In fact, high concentrations of black carbon in the Cretaceous-Tertiary boundary sediments suggest that the end of the age of the reptiles some 65 million years ago was associated with global fires that injected enormous quantities of soot particles into the atmosphere (*6*).

Today, the environmental impact of the burning of fossil fuels and biomass is felt throughout the world, and concerns about its consequences are prominent in the public's mind. Although the quantities of fossil fuels burned have been well documented, most biomass burning takes place in developing countries and is done by farmers, pioneer settlers, and housewives, for whom keeping records of amounts burned is not an issue. Biomass burning serves a variety of purposes, such as clearing of forest and brushland for agricultural use; control of pests, insects, and weeds; prevention of brush and litter accumulation to preserve pasturelands; nutrient mobilization; game hunting; production of charcoal for industrial use; energy production for cooking and heating; communication and transport; and various religious and aesthetic reasons. Studies on the environmental effects of biomass burning have been much neglected until rather recently but are now attracting increased attention (*7*). This urgent need has been recognized and will form an important element in the International Geosphere-Biosphere Programme (*8*).

In this article, we update quantitative estimates of the amounts of biomass burning that is taking place around the world and the resulting gaseous and particulate emissions and then discuss their atmospheric-chemical, climatic, and ecological consequences. Distinction should be made between net and prompt releases of CO_2. Net release occurs when land use changes take place by which the standing stock of biomass is reduced, for example, through deforestation. Biomass burning causes a prompt release of CO_2 but does not necessarily imply a net release of CO_2 to the atmosphere, as the C that is lost to the atmosphere may be returned by subsequent regrowth of vegetation. In either case, there is a net transfer of particulate matter and trace gases other than CO_2 from the biosphere to the atmosphere. Many of these emissions play a large role in atmospheric chemistry, climate, and terrestrial ecology.

Estimates of Worldwide Biomass Burning

In this section we derive some rough estimates of the quantities of biomass that are burned in the tropics through various activities, such as forest clearing for permanent use for agriculture and ranching, shifting cultivation, removal of dry savanna vegetation

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and firewood, and agricultural waste burning. In all cases, the available data are extremely scanty, allowing only a very uncertain quantitative assessment.

Clearing of forests for agricultural use. Two types of forest clearing are practiced in the tropics: shifting agriculture, where for a few years the land is used and then allowed to return to forest vegetation during a fallow period, and permanent conversion of forests to grazing or crop lands. In both cases, during the dry season, undergrowth is cut and trees are felled and left to dry for some time in order to obtain good burning efficiency. The material is then set on fire. The efficiency of the first burn is variable. Observations in forest clearings in Amazonia gave a burning efficiency of about 28% (*9*), similar to the value used by Seiler and Crutzen (*10*). This relatively low efficiency is due to the large fraction of the biomass that resides in tree trunks, only a small portion of which is consumed in the first burn. The remaining material may be left to rot or dry but is often collected and set on fire again. Adequate statistics are not available on how much of the original above-ground biomass is finally burned. Taking reburn into account, we assume that in primary forests some 40% is combusted (*9*). For secondary forests, which have been affected by human activities and contain smaller sized material, we assume that 50% is burned.

According to Seiler and Crutzen (*10*), shifting agriculture (also called slash-and-burn agriculture, field-forest rotation, or bush-fallowing) was practiced by some 200 million people worldwide in the 1960s on some 300 million to 500 million ha, with an annual clearing of some 20 million to 60 million ha and a burning of 900 to 2500 Tg dm, that is, 400 to 1100 Tg of C; of this, 75% takes place in tropical secondary forests and the remainder in humid savannas (dm = dry matter; 1 g dm ≈ 0.45 g of C). Originally, shifting cultivators typically practiced crop and fallow periods of 2 to 3 and 10 to 50 years, respectively. Because of growing populations and lack of forest areas, fallow periods in many regions have shortened so much that the land cannot recover to the required productivity, which causes shifting agriculture to decline (*11*). On the other hand, in other regions it may still be expanding. According to Lanly (*12*), some 240 million ha were under traditional shifting agriculture by the end of the 1970s. On the basis of these statistics, Hao *et al.* (*13*) estimated that ~24 million ha are cleared annually for shifting cultivation in secondary forests. This clearing exposes ~2400 to 3000 Tg dm, that is, 1000 to 2400 Tg of C, to fire and thus leads to the release of 500 to 700 Tg of C. We combine the two ranges into an annual C release rate from shifting cultivation of between 500 and 1000 Tg. In traditional shifting agriculture, no net release of CO_2 to the atmosphere takes place because the forest is allowed to return to its original biomass density during the fallow period. The estimated rates, therefore, mainly represent prompt CO_2 release. However, because of overly frequent burning, the affected ecosystems often cannot recover to their original biomass, so that a net release of C to the atmosphere does result.

Permanent removal of tropical forests is currently progressing at a rapid rate. This process is driven by expanding human populations which require additional land, by large-scale resettlement programs, and by land speculation. The global rate of deforestation is subject to much uncertainty. The tropical forest survey of the Food and Agricultural Organization (FAO) of the United Nations for the latter part of the 1970s (*12*) has been the basis of several studies on net CO_2 release to the atmosphere. It now appears that the FAO statistics significantly underestimated deforestation rates, which, furthermore, may almost have doubled over the past decade (*11, 14*). As the earlier work on tropical deforestation was clearly based on questionable information, we feel that there is little point in reviewing it. Instead, we will estimate the consequences of deforestation activities for trace gas emissions, using the statistics assembled by Myers (*11*) and Houghton (*14*). This is the only available database that may be up to date and has also been adopted by the Intergovernmental Panel on Climate Change (*15*). Although newer data have now been assembled by the FAO, unfortunately they have not been released in time to be included in the present review. The net CO_2 release to the atmosphere due to deforestation from these sources still allows for the wide range of 1.1 to 3.6 Pg of C per year (*14*) [this range is given because of uncertainty regarding the areal extent of deforestation (*11*) and the original and successional biomass loadings (*16*)]. As about 60% of the total biomass is located below ground, including soil organic matter, this net release of CO_2 implies that 0.5 to 1.4 Pg of C per year of biomass are exposed to fire. As only 40 to 50% of the CO_2 release is through combustion (the rest is by microbial decomposition of organic matter), the resulting prompt release of CO_2 to the atmosphere would be in the range of 0.2 to 0.7 Pg of C per year.

Tropical savannas and brushland, typically consisting of a more or less continuous layer of grass interspersed with trees and shrubs, cover an area of about 1900 million ha (*17*). Savannas are burned every 1 to 4 years during the dry season with the highest frequency in the humid savannas (*18*). The extent of burning is increasing as a result of growing population pressures and more intensive use of rangeland. Although lightning may start some fires in savannas, most investigators are convinced that almost all are set by humans (*4*). Only dried grass, litter, weeds, and shrubs are burned; the larger trees of fire-resistant species suffer little damage.

Menaut (*18*) has estimated that in the West African savannas 45 to 240 Tg of C per year are burned. The total area of this savanna region is 227 million ha, including 53 million ha of Sahel semidesert. No similarly detailed analysis on biomass burning has yet been attempted for other savanna regions. If we extrapolate to include all the savanna regions of the world (1900 million ha), we estimate that between 400 and 2400 Tg of C burn annually, and that most emissions are from the African continent. As, especially on the African continent, shifting cultivation also takes place in savanna regions, some double accounting could occur. The analysis by Seiler and Crutzen (*10*) indicates that a 30% correction may have to be applied to the above range, reducing it to 300 to 1600 Tg of burned C per year.

Fuel wood, charcoal, and agricultural waste. In the developing countries, fuel wood and agricultural waste are the dominant energy sources for cooking, domestic heating, and some industrial activities. It is difficult to estimate the amount of wood burned each year. The number given by FAO (*19*) for 1987, 1050 Tg dm, is certainly an underestimate because it includes only wood that is marketed. Scurlock and Hall (*20*) estimate that the annual per capita biofuel need (firewood, crop residues, dungcakes) is about 500 kg in urban and 1000 kg in rural regions, and that perhaps two-thirds of the rural energy use in China comes from agricultural wastes. Altogether, they estimate that 14% of the global energy and 35% of the energy in developing countries is derived from biomass fuels, equivalent to 2700 Tg dm or 1200 Tg of C per year. Because of rapidly increasing populations in the developing world, this energy need is growing by several percent per year. An analysis of the situation in India (*21*), however, indicates a biofuel consumption of only 350 kg per capita per year in rural and 160 kg per capita per year in urban areas, adding up to a total consumption rate of 230 Tg per year for the Indian population of 760 million. About half of the biomass burned was firewood, the other half was mostly dung and crop residues.

It is clearly very difficult to extrapolate from this information. If the partitioning of biofuel between fuel wood and agricultural waste products derived for India were representative for the rest of the developing world, more than 1050 Tg dm of firewood and roughly an equal amount of agricultural waste products would be burned worldwide, that is, together at least about 950 Tg of C per year, 20% less than the 1200 Tg of C per year estimated by Scurlock and Hall (*20*). On the other hand, if the estimate of 230 Tg dm per year of biofuel burning for the Indian population is extrapolated to the total population in the developing world, then the amount is only about 600 Tg of C per year. Altogether we will assume a range of biofuel burning of 600 to 1200 Tg of C per year, with about equal contributions from firewood and agricultural waste products.

Burning of agricultural wastes in the fields, for example, sugar cane and rice straw, and stalks from grain crops, is another important type of biomass burning. The amount of residue produced equals about 1700 Tg dm per year in the developing world and a similar amount in the developed world (*22*). It is difficult to estimate what fraction of this waste is burned. Rice straw makes up 31% of the agricultural waste in the developing world, and, at least in Southeast Asia, burning of rice straw in the fields is the preferred method of waste disposal (*23*). Sugar cane residues account for about 11% of agricultural waste and are mostly disposed of by burning. We very tentatively guess that at least 25% of the agricultural waste, about 200 Tg of C per year, are burned in the fields. Summarizing from the uncertain information that is available, we estimate that yearly some 300 to 600 Tg of C of firewood and 500 to 800 Tg of C of agricultural wastes are burned in the developing world. In the industrial world the corresponding figures are about one-tenth as large.

Prescribed burning and forest wildfires. It is interesting to compare the quantities of tropical biomass burned with those due to fires in temperate and boreal forests. Although individual wildfires may be large, because of fire-fighting efforts, the area burned per year is relatively small. Stocks (*24*) estimates that about 8 million ha of temperate and boreal forests are subject to wildfires each year.

Prescribed burning is commonly used for forest management. It serves mainly to reduce the accumulation of dry, combustible plant debris in order to prevent destructive wildfires. Because it is limited to North America and Australia and the area involved is only 2 million to 3 million ha per year (*10*), it has little impact on a global scale. Together some 150 to 300 Tg of C per year are burned by prescribed burning and wildfires, much less than through fires in the tropics.

Emissions to the Atmosphere

Table 1 summarizes the quantitative estimates of biomass burning in the tropics. We estimate that a total of 2700 to 6800 Tg of C are annually exposed to fires, of which 1800 to 4700 Tg of C are burned. The average chemical composition of dry plant biomass corresponds closely to the formula CH_2O. The nutrient element content varies with seasonal growth conditions; on a mass basis it is relatively low: about 0.3 to 3.8% N, 0.1 to 0.9% S, 0.01 to 0.3% P, and 0.5 to 3.4% K (*25*). Consequently, although the emissions from biomass combustion are dominated by CO_2, many products of incomplete combustion that play important roles in atmospheric chemistry and climate are emitted as well, for example, CO, H_2, CH_4, other hydrocarbons, aldehydes, ketones, alcohols, and organic acids, and compounds containing the nutrient elements N and S, for example, NO, NH_3, HCN, and CH_3CN, SO_2, and COS. The smoke also contains particulate matter (aerosol) consisting of organic matter, black (soot) carbon, and inorganic materials, for example, K_2CO_3 and SiO_2. In Table 2, we combine our estimates of global amounts of biomass burning with the emission ratios for various important trace species and derived global rates of pyrogenic emissions.

Table 1. Summary of the biomass exposed to fires, the total carbon released, the percentage of N to C in the fuel, and the total mass of N compounds released to the atmosphere by fires in the tropics.

Source or activity	Carbon exposed (Tg C/year)	Carbon released (Tg C/year)	N/C ratio (% by weight)	Nitrogen released (Tg N/year)
Shifting agriculture	1000–2000	500–1000	1	5–10
Permanent deforestation	500–1400	200–700	1	2–7
Savanna fires	400–2000	300–1600	0.6	2–10
Firewood	300–600	300–600	0.5	1.5–3
Agricultural wastes	500–800	500–800	1–2	5–16
Total	2700–6800	1800–4700		15–46

In spite of the large uncertainties, it is quite evident from Table 2 that biomass burning results in globally important contributions to the atmospheric budget of several of the gases listed (*26*). Because much of the burning is concentrated in limited regions and occurs mainly during the dry season (July to September in the Southern Hemisphere and January to March in the Northern Hemisphere), it is not surprising that the emissions result in levels of atmospheric pollution that rival those in the industrialized regions of the developed nations. This comparison applies especially to a group of gases that are the main actors in atmospheric photochemistry: hydrocarbons (for example CH_4), CO, and nitrogen oxides (NO_x). These gases have a strong influence on the chemistry of O_3, and OH, and thus on the oxidative state of the atmosphere. We will next discuss the most important emissions.

Carbon dioxide. Our estimates of the amount of biomass exposed to fire worldwide (2.7 to 6.8 Pg of C per year; Table 1) and the resulting prompt CO_2 release to the atmosphere (1.8 to 4.7 Pg of C per year) are larger than earlier estimates (*10, 13*). They are 30 to

Table 2. Estimates of emissions in teragrams of C, H_2, CH_3Cl, N, S, or aerosol mass per year (TPM, total particulate matter; POC, particulate organic carbon; EC, elemental carbon; K, potassium). Emission ratios for C and S compounds are in moles relative to CO_2; those for N compounds are expressed as the ratios of emission relative to the N content of the fuel; the emissions of TPM, POC, EC, and K are in grams per kilogram of fuel C. The emission ratios have been derived from information in (*26, 29–31, 36,* and *46*). In calculating the ranges of total emissions, we used only half the ranges of total C emissions (2500 to 3900 Tg of C per year) and the emission ratios (for instance, 7.5 to 12.5% for CO). A similar procedure was followed for the N compounds.

Element or compound	Emission ratio	Emission from biomass burning	Total emissions from all sources
All C (from Table 1)		1800–4700	
CO_2	≈90%	1600–4100	
CO	10 ± 5%	120–510	600–1300
CH_4	1 ± 0.6%	11–53	400–600
H_2	2.7 ± 0.8%	5–16	36
CH_3Cl	$1.6 \pm 1.5 \times 10^{-4}$%	0.5–2	2
All N (from Table 1)		15–46	
NO_x	12.1 ± 5.3%	2.1–5.5	25–60
RCN	3.4 ± 2.5%	0.5–1.7	>0.4
NH_3	3.8 ± 3.2%	0.5–2.0	20–60
N_2O	0.7 ± 0.3%	0.1–0.3	12–14
N_2	≤50%	≤11–19	100–170
SO_2	0.3 ± 0.15%	1.0–4.0	70–170
COS	0.01 ± 0.005%	0.04–0.20	0.6–1.5
TPM	30 ± 15 g/kg C	36–154	≈1500
POC	20 ± 10 g/kg C	24–102	≈180
EC	5.4 ± 2.7 g/kg C	6.4–28	20–30
K	0.4 ± 0.2 g/kg C	0.5–21	

80% of the fossil fuel burning rate of 5.7 Pg of C per year (*16*).

We caution again that the prompt release of CO_2 to the atmosphere is not the same as the net CO_2 release from deforestation. The latter is estimated at 1.1 to 3.6 Pg of C per year (*15*). However, these figures need to be reduced somewhat, as a fraction of the burned biomass is converted into elemental C (charcoal), which is not subject to destruction by microbial activity (*5, 10*). There is hardly any information available on charcoal formation in fires. Fearnside and co-workers determined that in two forest clearings in Amazonia 3.6% of the biomass C exposed to the fires remained in the partially burned vegetation as elemental C (*9*). To this must be added the elemental C that is released in the smoke (*27*), so that the total elemental C yield may be about 4% of the C exposed to fire, or alternatively 14% of the C burned. From observations on a prescribed burn in a Florida pine forest (*28*), an elemental C yield of 5.4% (3.6 to 7.4%) of the C exposed or 9% (6 to 16%) of the C burned can be derived. From this limited data set we adopt charcoal yields of 5 and 10% of the C exposed or burned, respectively. When these elemental C yields are applied to the estimate of biomass burning given above, a range of elemental C production of 0.2 to 0.6 Pg of C per year can be deduced, which thus may reduce the range of net CO_2 emissions of 0.5 to 3.4 Pg of C per year. This correction is extremely tentative because of the paucity of measurements on elemental C production from forest fires and the total absence of data on yields from savanna fires or agricultural waste burning.

CO, CH_4 and other hydrocarbons, H_2, CH_3Cl. Figure 1 shows the sequence of the emission of CO_2 (maximum in the flaming stage), CO (maximum in the smoldering stage), and of various other gaseous products from experimental fires conducted in our laboratory. The fraction of CO emitted depends on the fire characteristics: hot flaming fires with good O_2 supply produce only a few percent, whereas smoldering fires may yield up to 20% CO (*29–31*). Therefore, CO may serve as a marker of the extent of smoldering combustion, so that emissions of gases from smoldering combustion can be better estimated on the basis of emission ratios relative to CO rather than relative to CO_2. Our estimates show very large emissions of CO, between 120 and 510 Tg of C per year. The estimated global source of CO is close to 1000 Tg of C per year (*32*); biomass burning is thus one of the main sources of atmospheric CO. Because about 70% of the OH radicals in background air react with CO, biomass burning can substantially lower the oxidative efficiency of the atmosphere (which is mostly determined by the concentrations of OH), and thus can cause the concentrations of many trace gases to increase.

Methane contributes strongly to the atmospheric greenhouse effect; in this respect it has 20 to 30 times the efficiency per mole in the atmosphere of CO_2. It resides in the atmosphere long enough to enter the stratosphere. There, the oxidation of each molecule of CH_4 leads to the production of two molecules of H_2O; this process adds substantially to the stratospheric water vapor content. Because reaction with CH_4 also converts active Cl and ClO catalysts (which break down O_3) into inactive HCl, CH_4 plays a substantial role in stratospheric O_3 photochemistry. The pyrogenic emissions of CH_4, 11 to 53 Tg of C per year, may be about 10% of the global CH_4 source. On the basis of $^{13}CH_4$ isotope studies, the source of CH_4 from biomass burning was even estimated to be as large as 50 to 90 Tg per year (*33*), exceeding our estimated range of pyrogenic CH_4 emissions (Table 2). Stevens *et al.* (*34*) indicate that the biomass burning source of CH_4 may have been increasing by 2.5 to 3 Tg per year during the past decade; this rate suggests that global biomass burning may have been increasing by as much as 5% per year, thus contributing strongly to the observed increases of CH_4 by almost 1% per year (*32*).

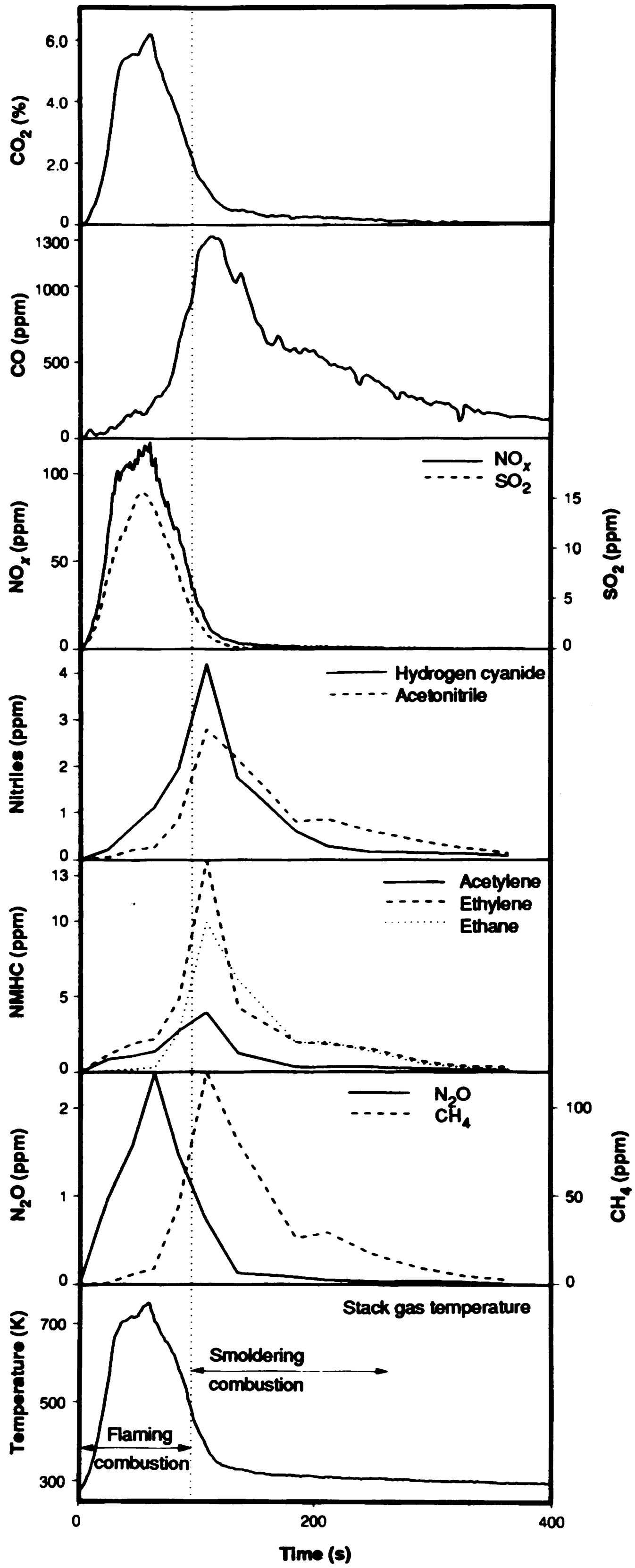

Fig. 1. Concentrations of CO_2, CO, and various other gases in the smoke from an experimental fire of Trachypogon grass from Venezuela as a function of time and the stack gas temperature. The dotted line separates the flaming phase from the smoldering phase. The flaming stage in this fire lasted for about 96 s. Concentrations are in percent by volume for CO_2, in volume mixing ratios (ppm) for the other species (1% = 10,000 ppm). Note that CO_2, NO_x, SO_2, and N_2O are mainly emitted in the flaming phase and the other gases in the smoldering phase; NMHC, nonmethane hydrocarbons.

For H_2, biomass combustion may contribute 5 to 16 Tg per year. Its global sources and sinks have been estimated to be about 36 Tg per year, mostly due to fossil fuel burning (*35*). Biomass burning may thus make a significant contribution to the global source of H_2, which plays a role in stratospheric photochemistry.

Our estimated emission range of CH_3Cl, from 0.5 to 2 Tg of Cl per year by biomass burning, is large in comparison with its destruction rate of about 2 Tg of Cl per year by reaction with OH radicals (*32*). The photochemical breakdown of CH_3Cl is a significant source for active Cl in the stratosphere, so that it plays a role in O_3 depletion. CH_3Cl is often considered to be of natural origin, emanating from the ocean. This view needs to be reconsidered (*26, 32*).

Nitrogen gases. Emissions of NO from biomass burning may be in the range of 2 to 6 Tg of N per year, about 10 to 30% of the input from fossil fuel burning and comparable to the natural NO sources: lightning (2 to 10 Tg of N per year) and soil emissions (5 to 15 Tg of N per year) (*32*). Therefore, biomass burning contributes significantly to total NO emissions. For N_2O, on the other hand, we now estimate that pyrogenic emissions are relatively small (0.1 to 0.3 Tg of N per year) (*36*), only a few percent of the global N_2O source of about 14 Tg of N per year (*32*). Earlier measurements of N_2O releases by biomass burning (*29*) have been biased by N_2O production in the collection devices.

The emissions of HCN and CH_3CN (together 0.5 to 1.7 Tg of N per year, and at a ratio of about 2:1) are significant, if not dominant, contributors to the atmospheric input rates of these compounds. The most important atmospheric sinks of HCN and CH_3CN, their reaction with OH, equals only 0.2 Tg of N per year for HCN and 0.02 to 0.2 Tg of N per year for CH_3CN (*30*). Consequently, other sinks must exist. Hamm and Warneck (*37*) proposed that these compounds may be taken up by the oceans. Another possibility is that they are consumed by vegetation, in which case they might serve as a minor source of fixed N. The atmospheric budget of NH_3 is not well known. Worldwide emissions are estimated to be in the range of 20 to 80 Tg of N per year (*32, 38, 39*), of which microbial release from animal excreta and soils makes up the largest fraction. The pyrogenic source (0.5 to 2.0 Tg of N per year) is thus only a few percent of the global source.

An important outcome of the burning experiments at our laboratory (*36*) is that only about 25% of the plant N is emitted as NO, N_2O, NH_3, HCN, and CH_3CN. At most 20% of the N may be emitted as high molecular weight compounds, and about 10% of it is left in the ash. Recent measurements have shown that the remaining fraction, as much as 50% of fuel N, is emitted as N_2 (*36*). Thus biomass burning leads to pyrodenitrification at a global rate of 10 to 20 Tg of N per year. This rate is 6 to 20% of the estimated terrestrial N fixation rate of 100 to 170 Tg of N per year (*39*) and therefore of potentially substantial significance. Most of the N loss occurs in the tropics, where it may lead to a substantial nutrient loss, especially from agricultural systems and savannas. Robertson and Rosswall (*40*) estimated that 8.3 Tg of N are emitted each year from West Africa into the atmosphere by burning, of which about 3.3 Tg could thus be N_2. This is almost three times their estimate of biological denitrification rate from the region.

Sulfur gases. In contrast to the N species, only relatively small amounts of SO_2 and aerosol sulfate are emitted. Biomass burning contributes only a few percent to the total atmospheric S budget, and only about 5% of the anthropogenic emissions. Still, because 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 could make a significant contribution to the S budget over remote continental regions, for example, the Amazon and Congo basins (*41*). Here, deposition may be enhanced five times because of tropical biomass burning.

Particles (smoke). Even though smoke is the most obvious sign of biomass burning, quantitative estimates on the amounts of particulate matter released are still highly uncertain. On the basis of an emission ratio of 30 g per kilogram of CO_2-C (*27*), we estimate that the emission of total particulate matter (TPM) is 36 to 154 Tg per year (Table 2). This amount may appear to be minor compared to the total emission of particulate matter of the order of 1500 Tg per year. However, much of these emissions consists of large dust particles, which only briefly reside in the atmosphere. The smaller smoke particles are much more long-lived and more active in scattering solar radiation. The C content of smoke particles is about 66% (*27*), which is consistent with the notion that they consist mostly of partially oxygenated organic matter. This composition leads to an emission of about 30 to 100 Tg of particulate organic C, which would be about 15 to 50% of the organic C aerosol released globally (*42*). The content of black elemental C in smoke particles from biomass burning is highly variable. In smoldering fires it is as low as 4% (weight percent carbon in TPM), whereas in intensively flaming fires it can reach 40% (*43*). We use a value of 18%, based on our work in Amazonia (*27*). From this and the estimate for global TPM emissions of 36 to 154 Tg per year, we obtain a source estimate for black C aerosol of 6 to 30 Tg per year. This value already exceeds the earlier estimate of 3 to 22 Tg per year for the emission of black C from all sources (*44*).

Atmospheric Chemical Effects

Long-range transport of smoke plumes. The hot gases from fires rise in the atmosphere, entraining ambient air. Frequently, clouds form on the smoke plume and usually reevaporate without causing rain. When the plume loses buoyancy, it drifts horizontally with the prevailing winds, often in relatively thin layers, which can extend over a thousand kilometers or more. The height to which the smoke plumes can rise during the dry season is usually limited in the tropics by the trade wind inversion to about 3 km.

The further fate of the smoke-laden air masses depends on the large-scale circulation over the continent in 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 intensifies, destroys the layered structure, and causes the pyrogenic emissions to be distributed throughout the lower troposphere. Finally, in the ITCZ region, smoke and gases from biomass burning may reach the middle and upper troposphere, perhaps even the stratosphere. Air masses from the biomass burning regions in South America are usually moving toward the south and southeast, because of the effect of the Andes barrier on the large-scale circulation. Here again, they may become entrained in a convergence zone, the seasonal South Atlantic Convergence Zone (SACZ), which becomes established in austral spring, when biomass burning is abundant. Indeed, the data from the space-borne MAPS (Measurement of Air Pollution from Satellites) instrument typically show high concentrations of CO in the mid- and upper troposphere near the ITCZ and the SACZ (*45*).

Results of chemical measurements from satellites, space shuttle, aircraft, and research vessels indicate that pyrogenic emissions are transported around the globe. Soot C and other pyrogenic aerosol constituents have been measured during research cruises over the remote Atlantic and Pacific (*46*). High levels of O_3 and CO have also been observed from satellites over the tropical regions of Africa and South America, and large areas of the surrounding oceans (*45, 47*).

Photochemical smog chemistry. Biomass fires emit much the same gases as fossil fuel burning in industrial regions: CO, hydrocarbons, and NO_x, the starting ingredients for the formation of O_3 and photochemical smog. Once such a mixture is exposed to sunlight, hydrocarbons, including those naturally emitted by vegetation, are oxidized photochemically first to various peroxides, aldehydes, and so forth, then to CO. This CO is added to the amount directly emitted from the fires and is finally oxidized to CO_2 by reaction with OH. High concentrations of hydrocarbons and CO have been observed during the burning season in the tropics (*27, 29, 48*). In the presence of high 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 O_3 (*29, 48*). The efficiency of O_3 formation, that is, the amount of O_3 formed per molecule of hydrocarbon oxidized, depends on the spread of the smoke plume and the chemical mix 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 (*49*). Increased concentrations of O_3 promote high concentrations of OH radicals and thus increase the overall photochemical activity of air masses affected by biomass burning. The effect may be enhanced further by the simultaneous emission of CH_2O [$\approx 2 \times 10^{-3}$ to 3×10^{-3} relative to CO_2 (*31*)], which is photolyzed in the tropical atmosphere within a few hours; this process leads in part to the production of HO_2 radicals via the formation of H and CHO. A similar effect may be caused by the photolysis of HONO, which may be emitted directly by the fires or formed by reactions on smoke particles (*50*).

High O_3 concentrations are produced in the plumes that extend over major parts of the tropical and subtropical continents during the dry season (*27, 29, 48, 51*). The highest concentrations, typically in the range from 50 to 100 ppb, are usually found in discrete layers at altitudes between 1 and 5 km, in accordance with the transport mechanisms of the burning plumes described above (Fig. 2). The concentrations at ground level are substantially lower and show a pronounced daily cycle with minima at night and maxima around midday. This cycle is controlled by the balance of O_3 sources and sinks: at night, O_3 consumption by deposition on the vegetation and reaction with hydrocarbons emitted by the vegetation and with NO emitted from soils reduce the concentration of O_3 near Earth's surface; during the day, these sinks are exceeded by photochemical O_3 formation and downward mixing of O_3-rich air. Also at ground level, O_3 volume mixing ratios in excess of 40 ppb are frequently measured during the dry season (*48*), similar to average values observed over the polluted industrialized regions of the eastern United States and Europe (*52*). Studies in temperate forest regions have linked such levels of O_3 pollution to damage to trees and vegetation, which has become widespread in Europe and North America (*53*). In view of the sharp increase of O_3 with altitude frequently observed in the tropics, the risk of vegetation damage by O_3 may be highest in mountainous regions, where O_3 concentrations above 70 ppb could be encountered. Ozone episodes with ground-level concentrations of 80 to 120 ppb must be expected to occur particularly during the dry season, when photochemically reactive air becomes trapped under the subsiding inversion layer (*54*). The regional ecological impact of high concentrations of phytotoxic O_3 on tropical vegetation and food production in the developing world is a matter of concern (*55*).

Perturbation of oxidant cycles in the troposphere. The global increase of tropospheric O_3, CO, and CH_4 concentrations, which is expected to continue in the future, is an indication of a fundamental change in the chemical behavior of the troposphere. 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 OH. The reaction chains involved are such that OH is consumed when the concentration of NO_x is low. This is the normal condition of most of the unpolluted troposphere. On the basis of the observed increase of CO and CH_4, it has been suggested that global decreases in OH, the primary sink for CH_4 and CO, could lead through a feedback mechanism to a further increase in CO and CH_4, and that this situation could produce an unstable chemical condition (*56*). Injection of large amounts of NO_x from biomass burning and other anthropogenic activities may counteract this feedback, because hydrocarbon oxidation in the presence of elevated amounts of NO_x creates additional O_3 and OH. This countereffect is, however, much more regionally limited because of the much shorter residence time of NO_x compared to that of CO and CH_4.

Model calculations (*57*) predict that a sixfold increase in regional OH concentrations in the boundary layer could occur as a result of deforestation and biomass burning in the tropics. There are two main reasons for this surprisingly large effect. One is that in the deforested regions NO_x is more easily ventilated to the atmosphere and a smaller portion reabsorbed in the less dense vegetation. The other is that removal of the trees eliminates the large emissions of isoprene (C_5H_8), which would normally react with and strongly deplete OH. We may, therefore, expect a strong enhancement of boundary layer O_3 and OH concentrations over tropical continental areas during the dry season, when vegetation is burned.

However, for the globe as a whole, it is likely that increasing CO and CH_4 emissions, with a large contribution from biomass burning, will lead to decreasing average OH concentrations and thereby to the buildup of the many gases that are removed from the atmosphere by reaction with OH. This change may be an extremely important development in global atmospheric chemistry.

Climatic and Ecological Effects

Climate change. With net global CO_2 emissions of 1.1 to 3.6 Pg of C per year, the clearing of the tropical forests may be responsible for up to 20 to 60% of the greenhouse warming caused by the CO_2 emissions from fossil fuel burning. Biomass burning also releases another greenhouse gas, CH_4. In this case, biomass burning accounts for only about 10% of the global CH_4 sources, but probably for a greater fraction of the increase in global emissions (*33*). Estimates of the temporal trends of CH_4 source strengths from 1940 to 1980 (*58*) suggest that the pyrogenic contribution to the increase in CH_4 emissions over that time period is 10 to 40%.

The climatic effect of the smoke aerosols is beyond current understanding because of the complex nature of the interactions involved. Aerosols can influence climate directly by changing Earth's radiation balance. They reflect sunlight back into space. Smoke particles also contain black (elemental) C, which may strongly absorb sunlight and thus cause a heating of the atmosphere and less penetration of solar energy to Earth's surface. Such an effect has an influence on the heat balance of the lower troposphere; it results in less solar heating of the surface, warming of the atmosphere, and more stable meteorological conditions. Robock (*59*) has shown that large daytime temperature drops can occur below smoke plumes from mid-latitude forest fires. Considering the great extent and expansion of tropical biomass burning, a widespread effect of this kind may well have masked the expected greenhouse temperature rise during the dry season on the tropical continents.

Because the equatorial regions, particularly the Amazon Basin, the Congo Basin, and the area around Borneo, are extremely important in absorbing solar energy and in redistributing this heat through the

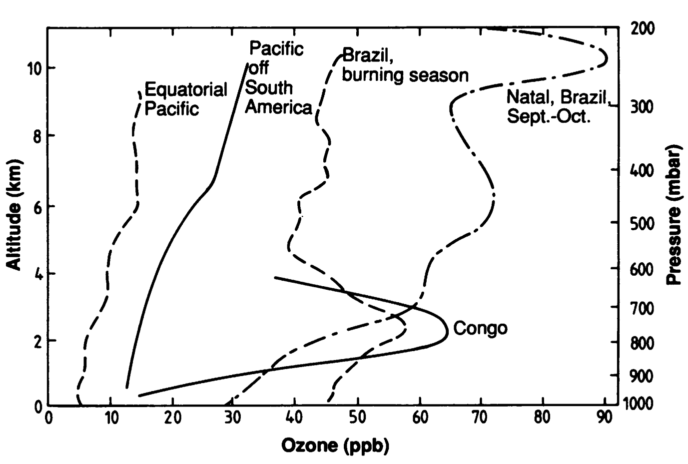

Fig. 2. Vertical profiles of O_3 in the tropical troposphere. The profile over the equatorial Pacific shows no influence from biomass burning), whereas the profile over the Pacific off South America suggests O_3 enhancement due to long-range transport from the tropical continents (*47*). The O_3 profiles over Brazil (*29*) and the Congo (*51*) show high O_3 concentrations at altitudes between 1 and 4 km due to photochemical production in biomass burning plumes. At higher altitudes, O_3 concentrations are also substantially enhanced, possibly also because of O_3 production by reactions in the effluents of biomass burning (*48*). [Adapted from (*47*) with permission of the author]

atmosphere, any change affecting the operation of these "heat engines of the atmosphere" may be highly significant. A matter of considerable interest is the influence of submicrometer-sized pyrogenic particles on the microphysical and optical properties of clouds and climate, an issue that has attracted considerable attention in connection with S emissions into the atmosphere (*60, 61*). Cloud droplets form on aerosol particles; these are called cloud condensation nuclei (CCN). The properties of the cloud depend on the number of available CCN: the more CCN, the more droplets that can form and the smaller the droplet size for a given amount of water. Clouds made up of smaller droplets reflect more sunlight back into space, and, because these clouds also are less likely to produce rain, cloud coverage also may increase. Because clouds are one of the most important controls on the heat balance of Earth, any large-scale modification of cloud properties is likely to have a strong impact on climate. Following proposals by Warner and Twomey (*62*) and by Radke *et al.* (*63*), recent studies have shown that many of the submicrometer smoke particles produced by biomass fires can serve as CCN (*64*). Aged particles show enhanced CCN activity as their surfaces become coated with water-soluble materials, especially by uptake of HNO_3 and NH_3.

The pyrogenic production of smoke particles (40 to 150 Tg per year) is of the same magnitude as the input of sulfate particles from the anthropogenic emission of SO_2 from fossil fuel burning ($\approx$70 to 100 Tg of S per year worldwide) (*65*). On a molar basis and because of their larger surface to volume ratio, the emissions of pyrogenic particles may be even larger than those of sulfate aerosol. Consequently smoke particles, in addition to affecting the radiative properties of clouds and Earth's radiation balance, may also disturb the hydrological cycle in the tropics, with potential repercussions for regional and possibly global climate. Altogether, the climatic impact of biomass burning in the tropics may be impressively large. Recent general circulation model calculations by Penner *et al.* (*66*) indicate the possibility of a net change in Earth's radiation balance by -1.8 W/m^2, about equal, but opposite to the present greenhouse forcing.

The potential changes in precipitation efficiency add to the perturbation of the hydrological cycle in the tropics caused by deforestation and desertification. Tropical forests are extremely efficient in returning precipitation 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 (*67*). A region such as 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 is often the case, is converted into an essentially unvegetated surface by erosion and loss of topsoil, water runs off more quickly and returns through streams and rivers to the ocean, allowing less recycling. Beyond the unfavorable consequences that such large-scale changes in the availability of water will have on human activities, such a modification of the hydrological cycle may itself perturb tropical weather and maybe even climate (*68*). Furthermore, through the introduction of hotter and drier conditions, less evapotranspiration and precipitation, and a lengthening of dry season, there will be a much greater risk of and need for periodic fires (*69*). Together with changing biospheric emissions, the decrease in precipitation and cloudiness and changes in other meteorological factors also have the potential to alter the chemistry of the tropical atmosphere in major ways.

Acid deposition. After acid rain had become a notorious environmental problem in Europe and North America, it came as a surprise to scientists to learn that it was also widespread in the tropics (Table 3): acid rain has been reported from Venezuela (*70*), Brazil (*71*), Africa (*72*), and Australia (*70, 73*). 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 (*74*). However, more recent evidence shows that acetic acid is produced directly by biomass burning and that both formic and acetic acid are chemically produced in the plumes (*75*). Nitric acid is formed photochemically from the NO_x emitted in the fires (*57*). Results from modeling the effects of biomass burning and a moderate amount of additional pollution, mostly connected with the activities related to logging and so forth, suggest that during the dry season pH values of $\approx$4.2 can be expected in the tropics as a consequence of the formation of nitric acid alone (*57*). For comparison, the mean pH in rain sampled throughout the eastern United States in 1980 was 4.3 (*76*) (Table 3).

Acidic substances in the atmosphere can be deposited onto plants and soils either by rain and fog (wet deposition) or by the direct removal of aerosols and gases onto surfaces (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 (*77*). Acid deposition can act on an ecosystem through two major pathways: directly 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 (*78*), except perhaps in fog and dew. Nevertheless, the issue deserves some attention, as tropical forests may be inherently more sensitive to foliar damage than temperate forests because of the longer average leaf life of 1 to 2 years, which promotes cumulative damage.

Alterations of nutrient cycles and effects on soil degradation. Savanna and agricultural ecosystems are frequently deficient in N, P, or S (*79*). When an area is burned, a substantial part of the N present in the ecosystem is volatilized. If this N were deposited again relatively nearby, this would cause no net gain or loss on a regional basis. If, however, as a result of fires, some 50% of the fuel N is emitted as N_2

(*30, 36*), a significant loss of nutrient N may result. In addition, long-range transfer of NO_x, NH_3, and nitriles to other ecosystems (savannas to tropical forests) depletes the fixed N reservoir of frequently burned ecosystems and thus provides a potential for long-term ecological effects. The budget of Robertson and Rosswall (*40*) for West African savannas implies that this loss of fixed N could deplete the fixed N load of these ecosystems in a few thousand years, a short time in comparison with the period during which humans have been present in these ecosystems. It may therefore be asked, to what extent enhanced N fixation can compensate for the loss of fixed N. This may indeed occur: laboratory research on tallgrass prairie soils has shown an enhancement of nonsymbiotic N_2 fixation after additions of available P in the ash from fires (*80*). Although the effects of biomass burning on the N cycle of the fire-affected ecosystems are most obvious, other nutrient elements, especially K, P, Mg, and S are also lost via smoke particles (*81*) in amounts that may have long-term, ecological consequences.

Regarding the C cycle, two issues appear to be of particular interest:

1) The burial of pyrogenic charcoal residues that are not subject to microbial oxidation even over geological time scales, and that thus constitute a significant sink for atmospheric CO_2 and consequently a source for O_2 (*10*). Because the risk of fires increases with the growing atmospheric O_2 content (*82*), on geological time scales this may establish a positive feedback loop, which favors O_2 buildup in the atmosphere.

2) The enhancement of biomass productivity of 30 to 60% or more after burning, despite the loss of nutrients, observed in some studies in humid savanna ecosystems (*83*). The results depend largely on burning practices, especially timing. Whether enhanced productivity may also increase the pool of organic matter in the soil is unknown. Too little is yet known about the biogeochemical cycling of savanna ecosystems and changes thereof. It was discovered only recently that natural tropical grasslands may be much more productive than hitherto assumed, with productivity comparable to that of tropical forests (*84*). With a strong growth of the populations living in savanna regions, there will most likely be more frequent burning in these ecosystems. Significant effects on the global C cycle are possible, either through enhanced sequestering of C as charcoal and root-produced soil organic matter, if optimum burning practices are adopted (our speculation), or through loss of soil C by overly frequent fires and practices that lead to land degradation.

Table 3. Rainwater pH and acid deposition at some continental tropical sites and in the eastern United States.

Site	pH		Rainfall (cm)	Deposition (kg H^+ ha/per year)	Reference
	Mean*	Range			
Venezuela					
San Eusebio	4.6	3.8–6.2	158	0.39	(*70*)
San Carlos	4.8	4.4–5.2			(*70*)
La Paragua	4.7	4.0–5.0			(*70*)
Brazil					
Manaus, dry season	4.6	3.8–5.0	240†	0.29	(*71*)
Manaus, wet season	5.2	4.3–6.1			
Australia					
Groote Eylandt	4.3				(*73*)
Katherine	4.8	4.2–5.4			(*70*)
Jabiru	4.3				(*73*)
Ivory Coast					
Ayame	4.6	4.0–6.5	179	0.41	(*72*)
Congo					
Boyele	4.4		185	0.74	(*72*)
Eastern United States	4.3	3.0–5.9	130	0.67	(*76*)

*Volume weighted. †Annual average.

Ecosystems that are not burned, for example, remaining areas of intact rain forest, will receive an increased nutrient input. Studies of rainwater chemistry in the central Amazon Basin suggest that as much as 90% of the S and N deposited there is from external sources, and that long-range transport of emissions from biomass burning plays a major role (*41*). The long-term effects of such increasing inputs of nutrients to the rain forests, in combination with growing acid deposition and O_3 concentrations, are not known.

In addition to the immediate volatilization of N during the burns, enhanced microbial cycling of N in the soils occurs after fires. Emissions of NO and N_2O from soils at experimental sites in the temperate zone after burning were observed to be substantially higher than from soils at unburned sites (*85*). This effect persisted for at least 6 months after the fires. Following burning on a Venezuelan savanna site, enhancements in NO emissions by a factor of 10 were found for the 4 days during which the measurements were made (*86*). Other studies have also shown that the fluxes of NO_x from soils are enhanced after conversion from forests to grazing land (*87*), but in these studies the effect of burning was not isolated explicitly. However, in more extensive studies, Luizão *et al.* (*88*) did not observe enhanced N_2O fluxes on sites that were only burned and cleared but found a threefold enhanced emission on 3- to 4-year-old pasture sites. According to these researchers, the enhanced emissions may be caused by increased input of oxidizable C from grass roots or rhizomes, or compaction of the soil surface by the cattle.

Although the above studies indicate that the emissions of trace gases increase after land disturbances, the total effect is complex and unclear. According to Robertson and Tiedje (*89*), denitrification ($N_2 + N_2O$ production) is high in primary forests and at early successional sites but much lower at mid-successional sites. Studies by Sanhueza *et al.* (*90*) in a Venezuelan savanna and by Goreau and de Mello (*91*) on a cleared forest site during the dry season showed that forested areas may emit more N_2O than secondary grassland ecosystems derived by deforestation. Thus, although disturbed tropical forest ecosystems may initially emit more N_2O, this may only be temporary and in the long run less N_2O may be emitted. The issue is, therefore, unclear. Much long-term research is needed to elucidate the effects of biomass burning on nutrient cycling and especially on N volatilization in the tropics. This research is particularly important as there are indications that the main contributions to the total atmospheric N_2O source come from the tropics (*92*).

Conclusions

Our, still very uncertain, analysis of tropical biomass burning indicates emissions from about 2 to 5 Pg of C per year. In comparison, the present net release of CO_2 due to tropical land use change is estimated to range between 1.1 and 3.6 Pg of C per year (*14*). Significant amounts of C may be sequestered as charcoal, which may reduce the net release by 0.2 to 0.6 Pg of C per year. Because of the great importance of biomass burning and deforestation activities for climate, atmospheric chemistry, and ecology, it is clearly of the utmost importance to improve considerably our quantitative knowledge of these processes.

Biomass burning is a major source of many trace gases; especially the emissions of CO, CH_4 and other hydrocarbons, NO, HCN, CH_3CN, and CH_3Cl are of the greatest importance. In the tropical regions during the dry season, these emissions lead to the regional production of O_3 and photochemical smog, as well as increased acid deposition with potential ecological consequences. On a global scale, however, the large and increasing emissions of CO and CH_4, the main species with which OH reacts in the background atmosphere, will probably lead to a decrease in the overall concentration of OH radicals and, therefore, to a decrease in the oxidation efficiency of the atmosphere. As the atmospheric lifetime of NO is only a few days, most of the atmosphere remains in an "NO-poor" state, where photochemical oxidation of CO and CH_4 leads to further consumption of OH. This in turn will enhance the atmospheric concentrations of CH_4 and CO, leading to a strong photochemical feedback.

Biomass burning is also an important source of smoke particles, a large amount (maybe all) of which act as CCN or can be converted to CCN by atmospheric deposition of hygroscopic substances. The amount of aerosols produced from biomass burning is comparable to that of anthropogenic sulfate aerosol. Through this process, the cloud microphysical and radiative processes in tropical rain and cloud systems can be affected with potential climatic and hydrological consequences.

An important recent finding is the substantial loss of fixed N that may be occurring because of biomass burning (pyrodenitrification). This loss appears to be of the greatest significance for savanna and agricultural ecosystems in the tropics and subtropics. The potential role of the savanna ecosystems in Earth's biogeochemical cycles deserves much more attention than it has been given so far. The savanna regions may play an important role in the global C cycle because of their large productivity, the potential interference of biomass burning with this productivity, and the formation of long-lived elemental C. The geological importance of this C as a sink for atmospheric CO_2 (and source for O_2) should be explored.

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Mechanisms in the Cycle of Violence

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Two questions concerning the effect of physical abuse in early childhood on the child's development of aggressive behavior are the focus of this article. The first is whether abuse per se has deleterious effects. In earlier studies, in which samples were nonrepresentative and family ecological factors (such as poverty, marital violence, and family instability) and child biological variables (such as early health problems and temperament) were ignored, findings have been ambiguous. Results from a prospective study of a representative sample of 309 children indicated that physical abuse is indeed a risk factor for later aggressive behavior even when the other ecological and biological factors are known. The second question concerns the processes by which antisocial development occurs in abused children. Abused children tended to acquire deviant patterns of processing social information, and these may mediate the development of aggressive behavior.

IN SPITE OF THE FACT THAT CHILD MALTREATMENT HAS occurred since the beginning of civilization (*1*), it was only several generations ago that modern society finally began to recognize the enormity of this problem (*2*). Testimony before the U.S. Congress indicates that in the United States alone, billions of dollars are spent every year in the medical, psychosocial, and social service treatment of physically abused children (*3*). Little is known empirically, however, of the long-term consequences of early abuse or of the mechanisms by which abuse might have an impact on behavioral development.

It is now becoming established that being the object of physical harm by an adult is a risk marker for the development of violent behavior toward others later in life (*4*). Early retrospective and clinical case studies are being supplanted by prospective, controlled studies to demonstrate this risk (*5*, *6*). For example, Widom (*7*) reported that individuals who had been identified by juvenile courts as abused or neglected during childhood were 42% more likely than controls to perpetuate this cycle of violence by obtaining a criminal record of violence as adults. Methodological problems aside, this literature has yet to resolve two major questions regarding this cycle of violence. These questions are considered in this article, and empirical findings are reported that shed light on this topic.

What Is the Risk Factor in Child Abuse?

The first question concerns possible related factors that might account for the increased risk that is associated with early physical harm. Almost all prospective studies in this area have followed children who have been brought to the attention of juvenile courts or human service agencies (*5*, *7*). These studies confound the experience of abuse with subsequent actions by these agencies, which usually involve separation of the child from her or his parents, foster home placement, labeling of the child and family, or other drastic measures that might account for the reported increased risk in this population. Also, by relying on agency reports, such studies include only a small, biased portion of all children who are physically harmed in early life. Interviews with national probability family samples reveal that a full 18% of children have been the object of a "severe violent act" (more serious than spanking or slapping) (*8*) by

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Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles

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