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Emissions of Atmospheric Trace Gases from Vegetation Burning [and Discussion]

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Emissions of atmospheric trace gases from vegetation burning

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Emissions from vegetation fires are recognized as important contributions to biogeochemical cycles of elements. A brief overview is given on emissions of the trace components CO, CH_4, and NO_x determined under various field and laboratory conditions. The influence of these emissions of trace gases on their global turnover is shown to be important. Finally, the emissions due to burning of fuelwood for traditional cooking is compared to the influences of emissions due to wild vegetation fires.

1. Introduction

Evidence on the existence of fire on our globe can be traced back into the geologic past. The Fulgurite, a mineral formed in sandy soils (Komarek 1971) which is produced by lightning strokes, demonstrates that all times thunderstorms existed and thus lightning would ignite fuel wherever present. Since the mixing ratio of oxygen in the atmosphere exceeded 13% approximately 350–400 Ma ago (Warneck 1988) and as soon as terrestrial vegetation appeared on Earth, vegetation fires can be expected to have occurred. Fusain, a substance resembling charcoal, found in coal and rocks rich in land–plant fossils, is also recognized as a product of palaeofire (Clark & Robinson 1993) and these marks of Fusain illustrate that subtropical and tropical regions have been affected by fires over millenia (Goldammer 1993). Especially, the existence of large fusain layers indicates that gigantic fires have taken place in Earth history (Komarek 1973). Fire is accepted as a tool linked to humanity's heritage (Pyne 1993), and has shaped most tropical savannas in prehistoric and present times (Schüle 1990; Stocks & Trollope 1993). Savanna biomes are constrained and stabilized by the presence of fire, whereas tropical rain forests are affected by fires only at long intervals and have been found to be highly vulnerable ecosystems to fire damage. Also, on a scale below of ecosystems, many indications can be found for the everlasting influence of fire. Several plant or tree species are known to depend on fire for their success. Eucalyptus in Australia, the Protea plants in Africa, the Sequoia in America among others gain advantage over other species by being better adapted to fire.

Our awareness of the prominent role of biomass burning emissions in influencing the composition of the atmosphere is very recent (Evans *et al.* 1974, 1977; Crutzen 1979), and several studies have assessed these impacts (e.g. Crutzen *et al.* 1985; Harriss *et al.* 1988, 1990; Hegg *et al.* 1990; Fontan *et al.* 1992; Kaufman *et al.* 1992; Ward *et al.* 1992; Hurst *et al.* 1994; Lacaux 1995). Spectacular forest and

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savanna fires are recognized as a worldwide phenomenon (Cahoon *et al.* 1992; Andreae 1993), and today their occurrence is common knowledge. However, their impact is most often only seen from a socioeconomic view.

2. Fire statistics and quantification

Fires arise from many factors. Today 70–90% of all vegetation fires are believed to be of anthropogenic origin. Causes among others are arson for hunting, surrogates for pesticides and insecticides, modification of land use, and simply inattentiveness. Lightning will be the predominant natural trigger for vegetation fires. However, in terms of this other 10–30%, one has to keep in mind, that anthropogenic and natural fires compete for the same fuel. Anthropogenically induced fires tend to occur at shorter time intervals and on smaller areas compared to natural fires.

Due to biomass burning, considerable amounts of gases and particulates are released. Several of these are greenhouse gases, most importantly CO_2, and CH_4, but also other polyatomic molecules which moderate the radiation budget of the atmosphere. Subsequent to the direct emission of combustion products, secondary pollutants can be formed during the transport in the plumes (e.g. ozone), which are also radiatively active and influence the oxidation capacity of the atmosphere.

For quantifying vegetation fires several aspects have to be noted. First, fires are reported by numbers. Then the area they shape, together with fuel density and composition, need to be known. Furthermore, prevailing meteorological conditions have to be taken into account as they control burning efficiency to a large extent. A variety of oxidized and reduced species can be released depending on burning conditions.

While areas being burnt are quite easily quantified, except in politically difficult areas, fuel loadings are the worst known numbers. Estimates easily differ by more than an order of magnitude. The following limits can be identified, however. Fuel loadings of 1 t ha^{-1} of dry matter and less do not support continuous burning. Fuel loads of 2–8 t ha^{-1} dry matter are reported for savanna areas (Menaut *et al.* 1991; all other fuel loading numbers, J. Goldammer, personal communication). For boreal areas approximately 20 t ha^{-1} are typically used, though up to 34 t ha^{-1} dry matter have been reported. It is clear that scaling up involves difficulties in defining the ecotype and in assessing appropriate fuel loadings. The assessing scheme is schematically combined in figure 1.

3. Carbon released to the atmosphere

Present day estimates on biomass burned annually and subsequent carbon release are combined in table 1*a*. Carbon content of fuel is taken as 0.45 of the dry matter, except for charcoal where a factor of 4 is used to account for the production process. The contribution of burning in tropical savannas dominates all other sources. The total estimated release of 4080 Tg C a^{-1} (T=Tera=10^{12}) due to vegetation burning may be compared to the estimated global fossil fuel emission of 6000 Tg C for the year 1990 (Climate Change 1992).

Uncertainties are especially large in emissions from Asian Taiga and Tundra areas. Though informations on vegetation burning in the Russian Federation have become available recently, underestimations are still suspected. Additionally,

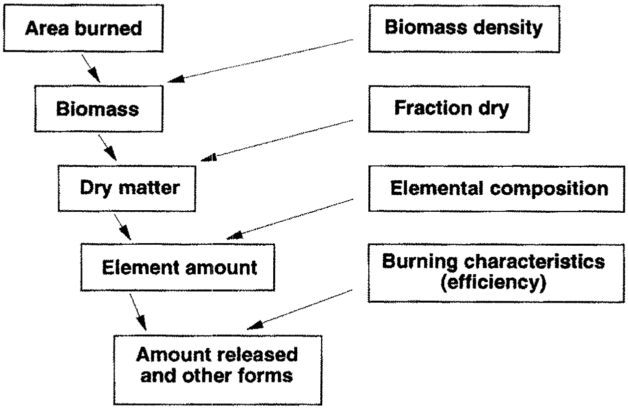

Figure 1. Scheme for quantification of emitted products from biomass burning.

fluctuations in emissions from year to year in boreal areas can be very large. So, for instance, for Canadian wildfires the total areas affected in the period from 1981 to 1991 range from 0.7 to 7.4 million hectare (Johnston 1992). Earlier estimates of global carbon emissions from biomass burning by Crutzen & Andreae (1990) do not differ much from the grand total in table 1*a*. These authors give a range of total released carbon of 1800 to 4700 Tg C a^{-1}. While their estimates of carbon released from forest burning remain in the same range as here (700–1700 Tg C a^{-1}), agricultural waste was estimated larger (500–800 Tg C a^{-1}) and biomass fuel smaller (300–600 Tg C a^{-1}). In table 1*b*, which was compiled by taking data from Weiss (1990) and Goldammer (1993), annually estimated burned and potentially burned (total available) biomass in tropical and subtropical areas are split up for different continents. Potentially much more biomass is present for burning, but only the ignited is counted for annually burned biomass. This difference between annually and potentially burned areas shows the possible range of interannual variation. Not all compilations on fire statistics cover the whole globe. Often only tropical and subtropical areas have been taken into account, so comparison between different assessments are not always possible. Table 1*c* shows the range of estimates of different authors on Africa only.

Biomass burned as domestic fuel represents the second largest contribution to carbon emissions from biomass burning, and is specified in more detail in table 2. As expected, these numbers are directly related to population. Different habits for fuel burning of rural and urban populations are taken into account to generate the numbers (Andreae 1993).

The amount of biofuel used in this way is expected to increase with population growth, which will, however, not fully change the figures as the fuel for wildfires will be diminished to some extent.

4. Emission factors and emission ratios

On average, the chemical composition of biomass is roughly 1 carbon, 2 hydrogen, and 1 oxygen atom. The mineral nutrient content normally varies between 0.3 and 3.8% of nitrogen, 0.1–0.9% of sulphur, 0.01–0.3% of phosphorus and 0.5–3.5% of potassium and further trace elements. Gases emitted during biomass burning are more or less oxidized combinations of these elements. The amount

Table 1. (*a*) *Global estimates of annual amounts of biomass burning and of the resulting release of carbon to the atmosphere*

(Factor 0.45 for dm → C, 4 for charcoal.)

burning source	biomass burned ($\mathrm{Tg\ dm\ a^{-1}}$) tropical	extratropical	carbon released ($\mathrm{Tg\ C\ a^{-1}}$)
forest	1260	1150	1080
savanna	3690	—	1660
charcoal	20	1	82
agric. waste	420	420	380
biomass fuel	1720	220	880
world total	7110	1800	4080

(*b*) *Annually (estimated) burned and potentially (total available) biomass in tropical and subtropical areas in* $10^{12}\ \mathrm{g\ a^{-1}}$ *(Weiss 1990; Goldammer 1993)*

	ecosystem	estimated burned amounts ($\mathrm{Tg\ a^{-1}}$)		total available biofuel ($\mathrm{Tg\ a^{-1}}$)	
Africa	forest	905		4835	
	savanna		3822		4251
South	forest	460		2693	
America	savanna		1496		3492
Asia	forest	199		1256	
	savanna		1852		2074
Australia and	forest	7		32	
Pacific Islands	savanna		761		1601
sum		1571	7931	8816	11418
grand total		9502		20234	

(*c*) *Annually burned biomass in* 10^{12} g *in Africa only (estimates of different authors)*

	forest	savanna	sum
Weiss 1990	140	3822	3962
Hao *et al.* 1990	390	2428	2818
Delmas *et al.* 1991	130	2520	2650

emitted of a specific species is given by the emission ratio of a particular chemical species, which depends on the type of biomass fuel burned and the burning efficiency. Starting from the amount of biomass available, its dry mass content and carbon composition in the fuel, the carbon amount released as CO_2 is calculated from the emission factor, which is defined as the amount of trace gas emitted per amount of fuel burned. Emission factors of g CO_2/kg dry matter vary to some extent. Though fuel composition has some effect, most often the fuel humidity

Table 2. *Biomass and charcoal used as domestic fuel*

region	population 1985 (millions)	fuel burned (Tg dm a^{-1})	charcoal (Tg dm a^{-1})
Asia	2820	1270	3.3
Africa	560	250	9.3
trop. America	430	190	7.5
Oceania	25	11	0
total tropics	3830	1720	20.1
U.S., Canada	260	100	0.5
Western Europe	380	49	0.2
USSR, east. Eur.	390	70	0.2
total extratrop.	1030	220	0.9
world total	4860	1940	21

and burning stage, i.e. burning or smoldering, governs this ratio. Lobert *et al.* (1991) report for laboratory experiments average emission factors of 83% carbon dioxide relative to the fuel carbon on a molar basis on average, but give a range of 49–99%. Delmas *et al.* (1991) use a range of 54–82%, while Andreae (1993) uses 88%, and Crutzen & Andreae (1990) 90%. Other forms of carbon emitted are CO, hydrocarbons, and soot. The latter is typically 1–2% of the exposed carbon (Kuhlbusch 1994.).

For estimates of emission amounts of other combustion products, the concept of emission ratios is used. This ratio is defined as dX/dCO or dX/dCO_2, where X denotes the molecule of interest and d the difference between the actual measurement value minus the background. Both CO and/or CO_2 are used as a reference depending on burning conditions, i.e. a dominance of flaming or smoldering combustion. This procedure is necessary to derive meaningful numbers from experimental data, as absolute concentrations of emitted compounds in smoke samples have little meaning. These absolute values simply represent varying degrees of dilution of the combustion products in ambient air. So assessments on amounts of emitted species are related to the emission factor of CO_2 and are calculated using the emission ratios. We combine in table 3*a*–*c* emission ratios of dCO/dCO_2, dCH_4/dCO and dCH_4/dCO_2 determined under various conditions in order to demonstrate the typical range of results obtained in those experiments.

Table 3*a* shows emission ratios of dCO/dCO_2 separated between field and laboratory studies. The span of the numbers given arises mainly from differing combustion conditions as was shown in burns of biomass under laboratory conditions (Lobert 1989), where the minimum values are linked to flaming and the maximum to smoldering. Under natural conditions these boundary conditions are rarely met. However, low emission ratios point to very vigorous burns, as were partly experienced during BASE-A (Kaufman *et al.* 1992), and SAFARI-

Table 3. (*a*) *Emission ratios of* dCO/dCO_2
(Values to be multiplied by 10^{-2}.)

field studies	min	mean	max
Greenberg *et al.* 1984	4.8	11.6	28
Crutzen *et al.* 1985	6	12	24
Andreae *et al.* 1988	5	8.5	8.8
DECAFE-88	1.9	2.9	3.9
Hegg *et al.* 1990	3.1	—	18.2
Bonsang *et al.* 1991	6	11	15.7
Cofer *et al.* 1991	4.7	—	12.1
Griffith *et al.* 1991	14.1	—	19.6
Kaufman *et al.* 1992	2.2	6.7	11.2
Ward *et al.* 1992	5	9.2	15.4
	4.2	8.2	15.6
Hurst *et al.* 1993	1.6	5.8	9.2
FOS/DECAFE-91, Helas *et al.* 1995	3	8	18
SAFARI-92, unpublished results	1.7	3.1	9
laboratory studies			
Darley *et al.* 1966	3.2	—	14
Gerstle & Kemnitz 1967	10	—	15
Boubel *et al.* 1969	5	—	25
Talbot *et al.* 1988	1.3	—	18
Lobert *et al.* 1989	1.8[a]	7.1	17[b]

[a] Flaming; [b] smouldering.

92. The BASE-A experiment took place in the Cerrado region of South America and SAFARI-92 in southern Africa. In both cases the fuel was extremely dry. Low emission ratios can also appear with high CO_2 concentrations not derived from combustion but from microbial activity in soil, as was experienced during DECAFE-88 in the Congo (Rudolph, personal communication). Values of *ca.* 6–12% can be assumed to be representative for most tropical and subtropical savanna regions, as was found by Greenberg *et al.* (1984), Crutzen *et al.* (1985), during ABLE-2A (Andreae 1988), during BASE-A and B (Kaufman *et al.* 1992; Ward *et al.* 1992), in South America, during FOS/DECAFE-92 in the savanna of west Africa (own results) and SAFARI-92 (own results). In all cases with higher emission ratios smoldering can be assumed to be dominant.

Emission ratios of methane, given in table 3*b*, are often normalized to both CO and CO_2. While normalization to CO refers to the fact that both species as reduced compounds are emitted predominantly during smoldering burning, normalization to CO_2 is more useful for assessment of total emitted amounts. Both emission ratios can be interrelated by

$$\frac{dCH_4}{dCO_2} = \frac{dCH_4}{dCO}\frac{dCO}{dCO_2},$$

Table 3. (*b*) *Emission ratios of* dCH_4/dCO
(Values to be multiplied by 10^{-2}.)

field studies	min	mean	max
Hegg *et al.* 1990	4.1	—	8.4
Kaufman *et al.* 1992	4.1	8.3	10.7
Ward *et al.* 1992	2.6	7.7	13.6
Hurst *et al.* 1993	1.0	6.8	16.7
FOS/DECAFE-91, Helas *et al.* 1995	—	5.3	—
SAFARI-92, unpublished results	—	5.3	—
laboratory studies			
Lobert *et al.* 1991	5.2	9.1	12.2

Table 3. (*c*) *Emission ratios of* dCH_4/dCO_2
(Values to be multiplied by 10^{-3}.)

field studies	min	mean	max
Greenberg *et al.* 1984	3	9	26
Crutzen *et al.* 1985	3	8	20
Bonsang *et al.* 1991	2.5	5.4	7.8
Cofer *et al.* 1991	2.7	—	12.1
Griffith *et al.* 1991	11	—	16
Kaufman *et al.* 1992	0.9	6.2	12
Ward *et al.* 1992	1.7	8.1	20.9
Hurst *et al.* 1993	0.8	3.9	11.4
FOS/DECAFE-91, Helas *et al.* 1995	—	4.2	—
SAFARI-92, unpublished results	—	1.7	—
laboratory studies			
Lobert *et al.* 1991	5.2	9.1	12.2

when applied to averages. Generally, dCH_4/dCO is around 7% with a range of 1–17%. Normalized to CO_2 the emission ratios range from 0.1 to 2% but centre around 0.5%. Again, the lower values point to efficient burns. This is also clearly demonstrated in table 4, from Delmas *et al.* (1991), where emission factors of carbon dioxide and methane are compared for different burning processes. The last column indicates emission ratios of 0.12% for savanna fires, while charcoal manufacturing produces a ratio of 3.3%.

To illustrate the close correlation of concentrations of hydrocarbons and CO in biomass burning plumes, figure 2*a*, *b* shows measurements from air samples taken during SAFARI-92 (own results). Figure 2*a* depicts the linear relationship between C_2H_4 and CO, while in 2*b* determinations of C_3H_6 and CO are shown.

Table 4. *Comparison of carbon dioxide and methane emissions during different combustion processes (from Delmas* et al. *1991)*

type of combustion	CO_2 emission factor/(g kg^{-1})	CH_4 emission factor/(g kg^{-1})	CH_4/CO_2 emission ratio
savanna fires	1370	1.3–2	0.0012
firewood burning	957	5–6	0.0057
forest fires	957	6–8	0.0073
charcoal making	641	15–27	0.0328

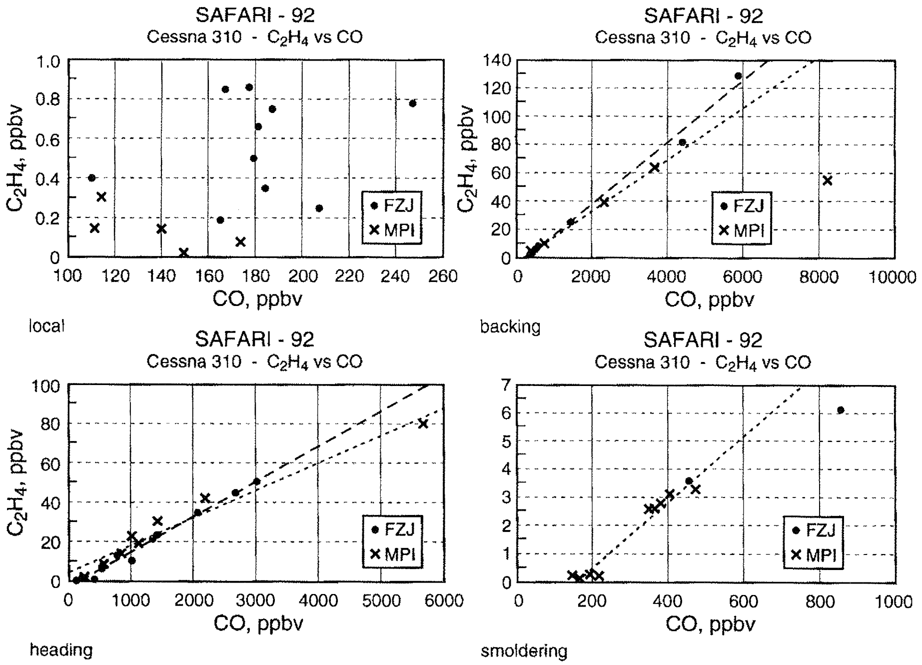

Figure 2. (*a*) Concentrations of ethene versus carbon monoxide in samples of biomass burning plumes taken during SAFARI-92 (own results).

In sum, as non-methane hydrocarbons (NMHC), the emission ratio for the group appears to be roughly equal in size to that of methane.

Because of their importance in atmospheric chemistry the group methyl halogenides is considered. These compounds are known to be photolysed in the stratosphere and then set free a halogen radical. These radicals in turn can deplete ozone in chain reactions. This group of compounds is also referenced to carbon monoxide and their emission ratios range from 9×10^{-4} for CH_3Cl, 8.3×10^{-6} for CH_3Br, and 2.6×10^{-6} for CH_3I. In table 5 (condensed from Andreae *et al.* 1995) fluxes from vegetation fires, calculated from these numbers, are compared to global flux estimates (WMO 1985). They indicate that biomass burning contributes a considerable share, 30% for methyl chloride and 20% for methyl bromide, to the total fluxes of these gases.

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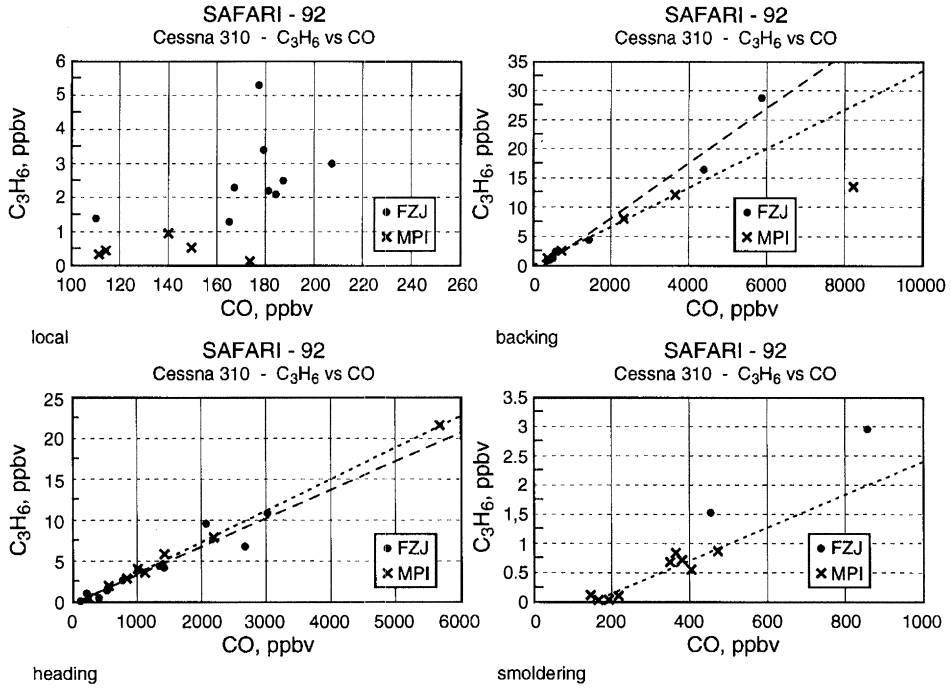

Figure 3. (*b*) Concentrations of propane versus carbon monoxide in samples of biomass burning plumes taken during SAFARI-92 (own results).

The emission factor of NO_x is expected to depend linearly on the nitrogen content of the fuel burned (Clements & McMahon 1980) and the NO_x/CO_2 ratio does not significantly change between flaming and smoldering (Lobert 1989). Therefore nitrogen oxides emission ratios do not vary much. Table 6 summarizes these emission ratios found under different conditions. In the upper part, marked with an asterisk, the values refer to dNO_2/dCO_2 values are given. Delmas *et al.* (1991) show that approximately 90% of the nitrogen oxides are emitted as NO, which agrees well with the differences found in the ratios of dNO_2/dCO_2 and dNO_x/dCO_2.

Ozone is formed easily in the photosmog conditions of plumes from biomass burning. This formation requires time (Chatfield & Delany 1990) and therefore the amount of ozone relative to a stable tracer in plume air is expected to increase to some extent with distance from the source. The production ratio dO_3/dCO from biomass burning is estimated as 0.3 (Andreae 1993) to 0.35 (Helas *et al.* 1992; Helas *et al.* 1995). So combining this number with CO emissions from vegetation fires, a production of approximately 10 Tmol O_3 a^{-1} is derived. This is about 30% of the global source strength and similar to the input of ozone through the tropopause from the stratosphere (Warneck 1988). The remaining 40% are assumed to be produced as secondary pollutants from industrial emissions.

5. Influence on global cycles

We combine the estimated global source strengths of biomass burning for various molecules in table 7, which is taken from Andreae (1993). CO_2 emissions from

Table 5. *Global mean emission ratios of methyl halides, reference species fluxes (see text), estimated global source strengths of methyl halides due to biomass burning, and their contribution to the total global fluxes*

(T denotes tera (10^{12}) and G giga (10^{9}).)

	global mean emission ratio 10^{-6}	reference species flux (mol a^{-1})	biomass burning (Gmol a^{-1})	% of global emissions
MeCl				
to CO	900	24.3 T	21.9	30
MeBr				
to CO	8.3	24.3 T	0.20	20
to MeCl	8500	21.9 G	0.19	
MeI				
to CO	2.6	24.3 T	0.06	—
to MeCl	2600	21.9 G	0.06	—

Table 6. *Emission ratios of* dNO_x/dCO_2

(Values to be multiplied by 10^{-3}.)

field studies	min	mean	max
Evans *et al.* 1977*	0.4	—	1.6
Griffith *et al.* 1991*	<0.4	—	0.6
Delmas *et al.* 1991*	—	0.14	—
FOS/DECAFE-91, Helas *et al.* 1995*	0.15	0.18	0.22
Crutzen *et al.* 1985	1.6	1.9	2.3
Hao *et al.* 1987	0.5	—	3.4
Andreae *et al.* 1988	0.5	1.5	3.5
Griffith *et al.* 1991	<0.9	—	1.7
Hurst *et al.* 1993	0.2	1.6	4.1
laboratory studies			
Gerstle *et al.* 1967	—	2.8	—
Lobert 1989	1.65	1.7	1.92

deforestation are separated from the total combustion of biomass burning. This distinction is drawn because CO_2 emissions from savannas are rapidly balanced by CO_2 absorption in grasslands which exhibit a fast regrowth a few months after the end of the dry season, whereas carbon released from deforestation causes a much longer perturbation of the atmosphere. It is estimated that more than 20% of the global fluxes of CO_2, CO, non-methane hydrocarbons, CH_3Cl, CH_3Br, NO_x, H_2, and O_3 are produced in vegetation fires.

The values reported by Crutzen & Andreae (1990) mostly show a wider span

Table 7. *Global source strength of biomass burning for various molecules (from Andreae 1993)*

	burning emissions (Tmol a^{-1})	% of global emissions
CO_2 (deforest.)	200	32
CO_2 (deforest.)	300	41
CO	24.2	26
CH_4	2.4	8
NMHC	3	36
CH_3Cl	0.1	55
N_2	1.4	26
N_2O	0.03	16
NO_x	0.7	24
NH_3	0.4	12
SO_x	0.08	1.2
COS	0.003	8
H_2	8	45
O_3	9	39

but do not differ in orders of magnitude. Emission ratios for many compounds just are better defined now. From these numbers the importance of vegetation fires for biogeochemical cycling is obvious. Most of the gases given in table 7 have residence times exceeding a week. So spread of these combustion products can be expected over several thousand kilometres, which also means across oceans. Fishman *et al.* (1991) identified from satellite analyses widespread ozone pollution with origins from Africa extending to both Australia and South America.

The emitted species exert a strong influence on the chemistry of the troposphere. On a local scale, elevated NO_2 levels may suppress the OH levels by scavenging and producing nitrates (Crutzen & Carmichael 1993). On regional scales, fires increase ozone mixing ratios and consequently also increases OH. However, CO consumes OH in a slow process, so that vegetation fires on a global scale should depress OH concentrations (Crutzen & Carmichael 1993). Additionally, several of the emitted species can be expected to enter the stratosphere, for instance methyl halides.

6. The influence of traditional cooking and wasteburning

The contribution of emissions of biofuel as used for traditional cooking and heating has been pointed out (table 2) as 880 Tg C annually. Agricultural waste burning was estimated to contribute 380 Tg C a^{-1}. This latter number is to some extent connected to home use, as in many areas of the world energy use comes from agricultural waste. These numbers referred to 1985 and were at that time approximately 20% and 10% of the world total release of carbon from biogenic sources. With increasing population, however, the need for fuel is expected to increase. Andreae (1993) had estimated an annual demand of 500 kg fuel per capita, which is an intermediate value between 160 given by Joshi (1991) for

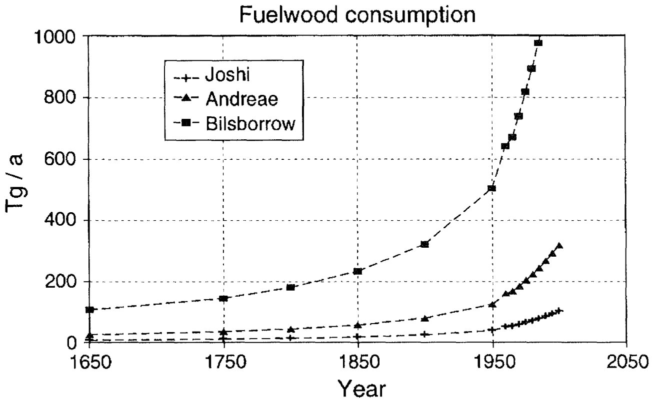

Figure 4. Estimated global biofuel consumption according to Joshi, Andreae, and Bilsborrow (see text).

urban India and 2000 for rural Sudan (Bilsburrow & DeLargy 1991). Combining this number with an assumed global population of 7.6–9.4 $\times$ 10^9 for the year 2025 (Climate Change 1992) one derives a consumption 3.8–4.7 Pg fuelwood a^{-1}, corresponding to an emission of 1.7–2.1 Pg C a^{-1}. This predicted increase is shown in figure 3, where also the two other fuel consumption estimates by Joshi and by Bilsborrow and DeLargy are added.

Biofuel emissions are expected to remain approximately at a 20% level or fall back to 15% of the fossil fuel emissions, which are estimated as 10.7 Pg C for the year 2025. Thus the absolute burden of trace compounds to the atmosphere is likely to increase due to basic energy needs.

It is useful to compare the need for biofuel to the net primary production rate, which is defined as the rate of storage of organic material in plant tissue resulting from the uptake of CO_2 in excess of that released again by respiration. As a sum over all ecosystems a range of 50–60 Pg C a^{-1} is expected (Warneck 1988, and references therein). On a global scale, this seems sufficient to provide biofuel, since savannas, tropical rain forests and seasonal forests contribute roughly the half of it. However, it does not necessarily follow that adequate amounts of biofuel can be transported to population centres.

7. Conclusion

Despite of uncertainties in the analysis of the total contribution of biomass burning to overall emissions, it has become clear in recent years that vegetation burning is an important source of trace gas species. The quantification of the burned biomass must take into account all types of fuel (savanna, forest, farm wastes, domestic fires, etc.) and their proper physical and chemical characteristics which determine their burning conditions, and thus the compounds emitted into the atmosphere. For several important greenhouse gases the burning of vegetation contributes significantly to their global emissions.

I thank my collegues for many helpful discussions when preparing this contribution.

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Discussion

W. G. CHALONER (*Royal Holloway College, London, U.K.*). My question relates to a product of vegetation burning, but not strictly to gaseous emissions. Wildfire produces charcoal by pyrolysis of wood and other plant material, in addition to the emission of gases and particulate matter. Charcoal is to all practical purposes 'unbiodegradable'; it is also chemically inert and physically robust, but brittle. These properties mean that the charcoal residue of wildfire is likely to be transported out of the catchment where it was produced, without being broken down by the action of microorganisms. Its eventual fate is to be buried in lake or marine sediments. That is, it is effectively taken out of circulation in the carbon cycle. From Dr Helas's investigation of the products of wildfire, is there any evidence as to the fraction of the biomass following an 'average' forest fire, which becomes converted to charcoal?

G. HELAS. Professor Chaloner is correct. 'Black' carbon is 'unbiodegradable'. The amount of black carbon (BC) formed is either related to the CO_2 releases or to the carbon exposed. BC/CO_2-ratios are estimated to 7–15% for shifting agriculture, 7–15% for permanent deforestation, 7–15% for temperate and boreal forests, 1–3% for savanna fires, 3–5% for firewood, and 1–3% for agricultural waste. The total amount of black carbon formed per annum is estimated to 67–136 Tg C (from Kuhlbusch 1994).

J. A. PYLE (*Department of Chemistry, Cambridge, U.K.*). The estimated global warming Dr Helas shows for the aerosol is quite high, as he has indicated. How does the estimate come about? Presumably, for example, the result is very sensitive to the altitude assumed for the aerosol.

G. HELAS. The estimated radiative climate forcing is rather high. The estimates have been taken from Andreae (1995).

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