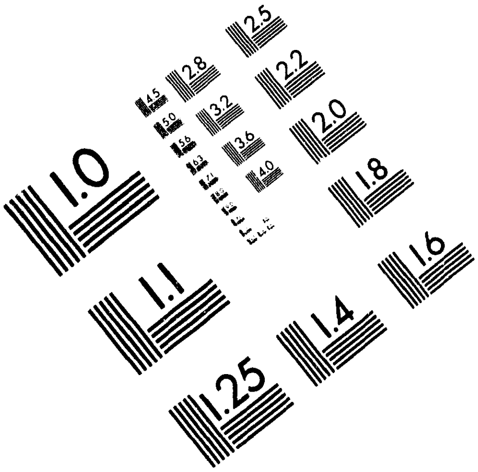

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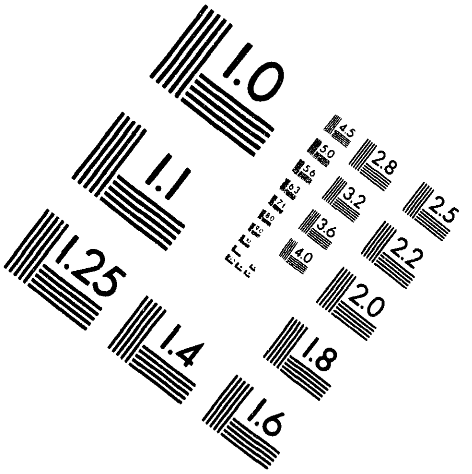

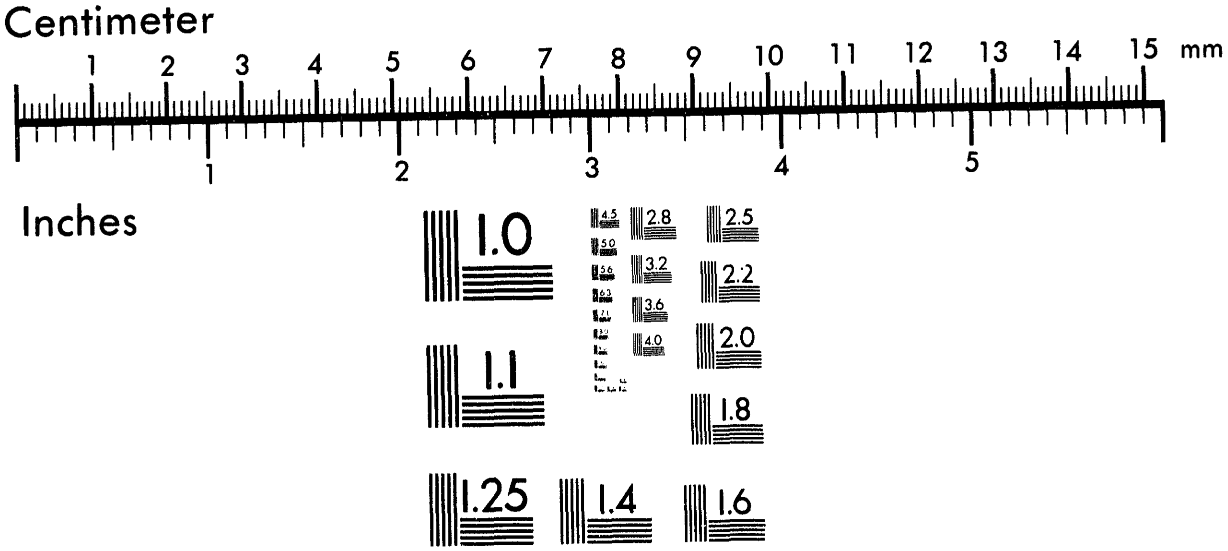

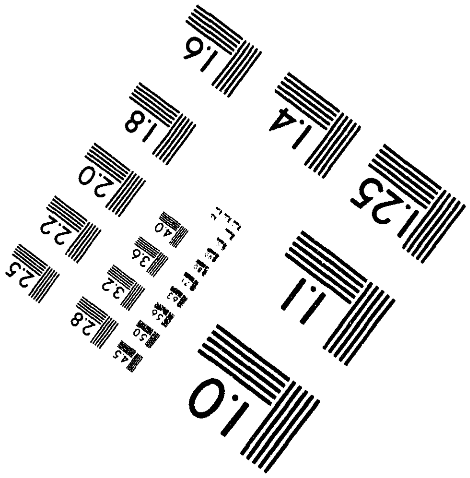

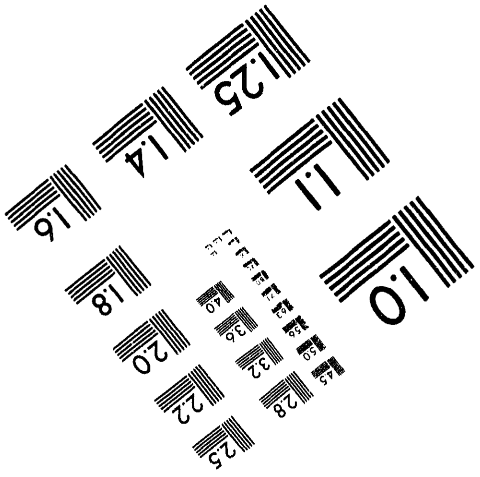

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Impact of Biomass Burning on the Atmosphere

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1. Introduction

Fire has played an important part in biogeochemical cycling throughout much of the history of our planet. Ice core studies have been very beneficial in paleoclimate studies and constraining the budgets of biogeochemical cycles through the past 160,000 years of the Vostok ice core. Although to date there has been no way of determining cause and effect, concentration of greenhouse gases directly correlates with temperature in ice core analyses. Recent ice core studies on Greenland have shown that significant climate change can be very rapid on the order of a decade (Mayewski et al., 1993). This chapter addresses the coupled evolution of our planet's atmospheric composition and biomass burning. Special attention is paid to the chemical and climatic impacts of biomass burning on the atmosphere throughout the last century, specifically looking at the cycles of carbon, nitrogen, and sulfur. Information from ice core measurements may be useful in understanding the history of fire and its historic affect on the composition of the atmosphere and climate.

2. History of Fire

The relationship between the atmosphere, life and fire began about 4.5 billion years ago, at the time when the earth was being formed. The atmosphere and ocean formed as a result of release of gases originally trapped beneath the planet's surface. These gases, including water vapor and carbon dioxide which are greenhouse gases, can trap heat and keep the mean temperature of the earth above the freezing point of water. Without these greenhouse gases the oceans would have frozen solid, and the planet would be incapable of producing life. Molecular nitrogen was also released volcanically at that time. Thus, the early atmosphere contained all of the necessary elements of life, carbon, oxygen, nitrogen and hydrogen. As atmospheric lightning and solar radiation struck the early atmosphere complex organic molecules such as formaldehyde and hydrogen cyanide were formed. In the early ocean these molecules combined to form long-chained organic molecules which eventually formed amino acids and later living systems.

At that time, (roughly 3.5 billion years ago) life was limited to the oceans which provided protection from the sun's deadly ultraviolet radiation. Eventually some species developed the unique capability of producing its own food by combining carbon dioxide and water in the presence of sunlight. A byproduct of this process, photosynthesis, is the release of molecular oxygen gas. Photosynthetic oxygen began to build up in the atmosphere. Oxygen in the atmosphere reacts with sunlight to form ozone. Ozone is the only gas found naturally that can absorb the lethal ultraviolet radiation from the sun. About 600 million years ago there was enough oxygen built up in the atmosphere to produce enough ozone to shield the surface of the earth. For the first time in the earth's history life could leave the oceans and move onto the land. Now there exists a situation where biomass (a combustible fuel) thrives in a dry environment with oxygen present. This is the natural recipe for fire on our planet which has existed ever since.

The interaction of natural wildfires and respiration were instrumental in controlling the CO_2 concentration in the atmosphere for most of the earth's history. Production of organic matter by plants supplied the potential for wildfires, and climate and ecological parameters established a natural fire frequency. Eventually however, humans overcame their fear of fire and learned to use wildfires to collect and kill game. Later they mastered fire themselves and used it as a tool in food preparation, hunting, and landscape control. To this day humans continue to use biomass burning to serve a variety of purposes:

1) clearing land for agriculture
2) control of weeds and brush on crop lands
3) nutrient regeneration in crop or grazing lands
4) controlled fires in forest
5) energy production (including charcoal production)

In present times most of the biomass burning is anthropogenic with only a small percentage started naturally by lightning.

3. Geographical distribution of biomass burning

The geographical distribution of biomass burning has been discussed by several authors in varying detail. Seiler and Crutzen (1980) were the first and gave a qualitative description of the geographic arrangement. Andreae (1991) presents a review as well. Hao et al. (1990) provide 5° latitude by 5° longitude gridded information for the tropics only. Dignon et al. (1991) and Dignon (1988) have estimated the amount of biomass burning on a 1°×1° grid globally totalling 7660 Tg dm annually. A summary of these author's results for individual biomass types is shown in Table 1. The fact that the values seem to agree fairly well should not necessarily give the reader confidence in the accuracy of the estimates. The similarity in the estimates is based on the fact that each of the authors have used the same input data to obtain their estimates. These include estimates of land-use conversion by Myers (1980) and Lanly (1982), and the density of biomass in each region given by Whittaker and Likens (1975). If we consider other more recent estimates of biomass density, e.g. Olsen et al. (1983) these estimates could be somewhat reduced.

Most of the biomass burning occurs during the dry season in the tropics with roughly 80 percent between 25°N and 25°S (Dignon and Penner, 1991). Table 2

Table 1. Global estimates of biomass burning and the resulting release of carbon to the atmosphere.

Source	Biomass Burned (Tg dm/yr)				C Released (Tg C/yr)
	Seiler and Crutzen[a]	Hao et al.[b]	Andreae[c]	Dignon[d]	
Tropical Forest	2420	1260	1260	1230	550-1090
Savanna	1190	3690	3690	3470	540-1660
Temperate/boreal forest	280	-	280	520	130-230
Fuel wood	1050	620	1430	1880	280-850
Charcoal	-	-	21	-	30
Agricultural waste	1900	660	2020	1360	300-910
Tundra	-	-	-	4	2
World total	6840	6230	8700	7660	1800-4740

[a] Seiler and Crutzen (1980)
[b] Hao et al. (1990)
[c] Andreae (1991)
[d] Dignon and Penner (1991), Dignon (1988)

Table 2. Regional distribution of biomass burning and the resulting carbon release to the atmosphere.

Region	Biomass Burned (Tg dm/yr)					C Released Tg C/yr
	Forest	Savanna	Fuel Wood	Agricultural Waste	Regional Total	
America	630	1210	310	115	2265	1020
Africa	460	2140	430	490	3520	1580
Asia	420	20	1100	750	2290	1030
Europe	30	-	40	-	70	30
Oceania	250	100	2	5	~360	160

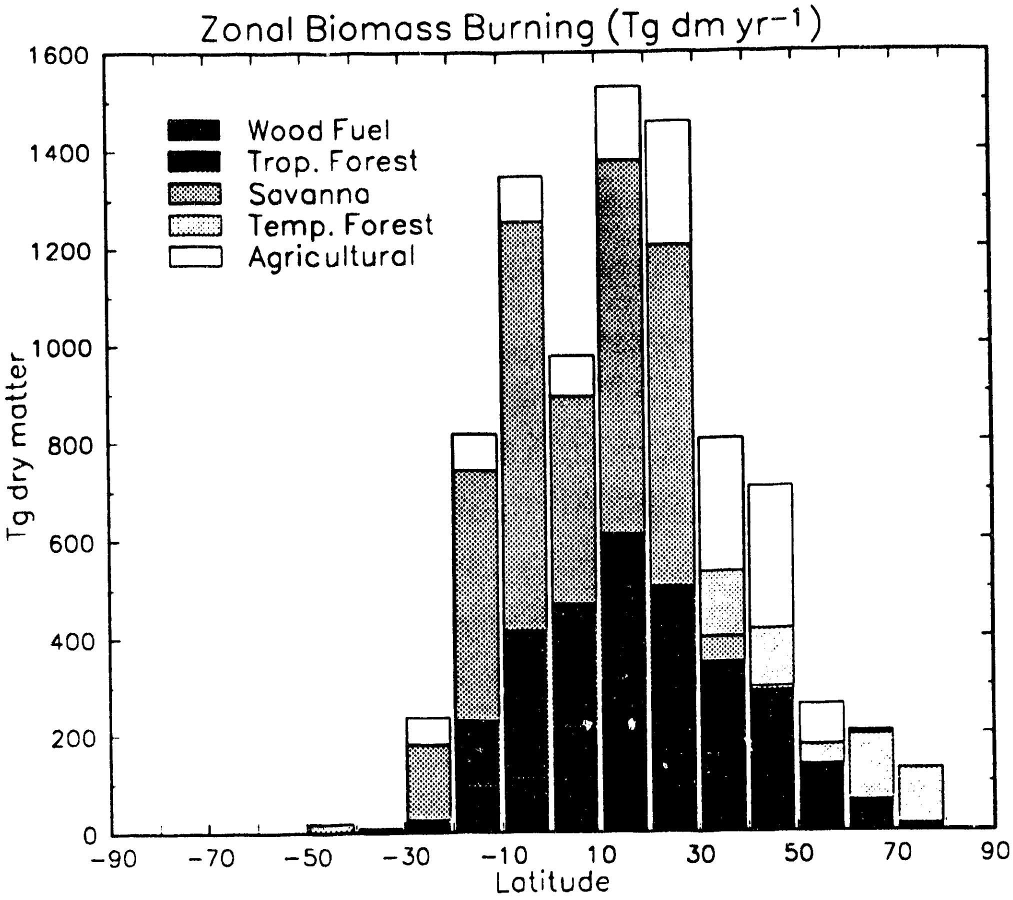

Figure 1. Zonal estimates of annual biomass burning in Tg dm from wood fuel consumption, tropical forest fires, savanna burning, temperate forest fires, and agricultural burning.

gives a regional description while Figure 1 gives the zonal totals for each biomass type including wood fuel. Based on the work of Hao et al. (1990) and Lacey et al. (1982) it is estimated that less than 20 percent of the biomass burning in the southern hemisphere occurs between the months of October through March. In the northern hemisphere, tropical burning is predominantly between October and March, while at higher latitudes April to September is the dominant burning season.

4. Environmental impact of biomass burning emissions

4.1 Carbon dioxide (CO_2)

Burning of organic materials produces water vapor and carbon dioxide as the primary products with other trace emissions as well. Until recent times the natural processes of respiration, photosynthesis and natural fires controlled the concentration of carbon dioxide on our planet. This equilibrium can be shifted out of balance if the biomass is burned and not rapidly replaced by regrowth. Thus CO_2 which is added to the atmosphere and remains there until it is removed by some other process. There it can contribute to the CO_2 greenhouse effect and global climate change. Regions of biomass burning today experience both of these phenomena. When savanna regions are burned the vegetative regrowth is quick, replacing the carbon in the savanna plants through photosynthesis. Consequently a net CO_2 balance is maintained. On the other hand, tropical rain forests are being destroyed and converted for alternative land use, releasing most of the carbon stored in the plants into the atmosphere (Houghton, 1991). Temperate forests fall into both carbon regimes depending on location.

Detwiler and Hall (1988) propose that only about 15% of the net CO_2 emissions forest fires are released during the burn. The remainder is released slowly over the next few years either by subsequent burnings or by microbial decomposition. They also expect an additional 25% of the net CO_2 release may result from the oxidation of organic matter in the cleared forest soils. The range of estimates shown in Table 1 for the gross carbon release are from 1800 to 4740 Tg C/year. Even if we assume that one half of that carbon is recycled, this is still comparable in magnitude to the 5200 TgC/yr released from fossil fuel burning. From this Andreae (1991) concluded that biomass burning/land use conversion is responsible for 25 percent of the global CO_2 greenhouse effect from human activities.

4.2 Other carbon species

Although most of the carbon released from biomass burning is given off in the form of CO_2 there is some carbon emitted in other forms due to non-complete combustion. These are primarily carbon monoxide (CO), methane (CH_4), and non-methane hydrocarbons (NMHC). The fraction of emissions of these species is dependent on the characteristics of the fire. The data in Table 3 gives estimates of

Table 3. Comparison of global emissions of carbon species from biomass burning with emissions from all sources.

Species	Biomass Burning (Tg C/yr)[a]	All sources (Tg C/yr)	Biomass Burning (percent)
CO	350	1100[b]	32
Methane	38	520[c]	7
NMHC	24	550[d]	4

[a] Andreae (1991)
[b] Penner (1993)
[c] Lelieveld et al. (1993)
[d] Singh and Zimmerman (1992); Kanakidou and Crutzen (1993)

the emissions of these trace gases from biomass burning. It also provides a comparison between biomass sources and the total emissions from all sources.

4.3 Nitrogen species

Nitrogen is present in plant biomass and is released during burning through pyrolytic decomposition. The nitrogen can then be oxidized either partially or completely depending on the fire characteristics. Nitric oxide (NO) is the most abundant reactive nitrogen species emitted during biomass burning whereas a large percentage of the nitrogen originally present in the fuel is given off as molecular nitrogen (Lobert et al., 1991). Other reactive nitrogen species emitted include nitrogen dioxide (NO_2), nitrous oxide (N_2O) and Ammonia (NH_4). Table 4 gives recent estimates of the amount of each nitrogen species emitted from biomass burning and the relative fraction of total emissions annually.

NO and NO_2 are also precursors to acid rain which is deposited in the form of HNO_3. Lacaux et al. (1991) have measured the concentration of nitrogenous compounds in rain water in the equatorial forest of Africa. The concentration during the dry savanna burning season is observed to be 2 to 3 times higher than in the wet season in the equatorial regions of Africa. Keller et al. (1991) has also shown a moderate influence of the rain water HNO_3 content from vegetation fires in

Table 4. Comparison of global emissions of nitrogen species from biomass burning with emissions from all sources.

Species	Biomass Burning (Tg N/yr)	All sources (Tg N/yr)	Biomass Burning (percent)
N_2O	0.8[a]	13[b]	6
NO_x	9[c]	42[c]	21
Ammonia	5.3[a]	44[d]	12

[a] Andreae (1991)
[b] Bolle et al. (1986)
[c] Dignon et al. (1991)
[d] Andreae et al. (1989)

Amazonia. It is unknown at this time whether the increased acidity has had any effect on the ecosystems of the region.

4.4 Ozone (O_3)

With the mixture of gases mentioned above including CO, hydrocarbons, and oxides of nitrogen we have the necessary ingredients for photochemical smog. These species combine in the presence of sunlight to form the production of tropospheric ozone. Watson et al. (1990) have shown that concentrations of tropospheric ozone off the western coast of Africa in the South Atlantic are of the same magnitude as those expected downwind of major industrial/urban centers in the northern hemisphere. Browell et al. (1988) have also measured ozone concentrations over the Amazon exceeding 50 ppbv during the dry/burning season compared to <12 ppbv during the wet season (Browell et al., 1990). It is presumed that the increased ozone observed in the "remote" tropical South Atlantic is due to the combination of photochemical production from NO_x, CO and hydrocarbons emitted from biomass burning over Africa and South America and advective transport.

Aside from being a pollutant harmful to life, the increase of tropospheric O_3 concentration in the tropics is also a concern because of its efficiency as an infrared absorber. According to Ramanathan et al. (1985) tropospheric O_3 increases are responsible for 15% of the overall greenhouse warming. The infrared greenhouse warming is expected to be more pronounced over tropical latitudes and according to Andreae (1991) tropospheric O_3 produced from biomass burning is responsible for up to 50 percent of the expected greenhouse warming due to tropospheric O_3.

4.5 Sulfur species

Sulfate is not volatile at the temperatures experienced in biomass fires consequently only about 50 percent of the sulfur content of the plant matter is emitted. This is primarily the sulfur that is organically bound in the amino acids and proteins of the plant. Most of this organically bound sulfur will be oxidized to gaseous sulfur dioxide (SO_2) and to a small extent carbonyl sulfide (COS). SO_2 is a pollutant, a precursor to acid rain, and a dominant contributor of tropospheric aerosol after its chemical conversion to $SO_4^=$; however the amount of SO_2 attributable to biomass burning compared to the total global flux is small (see Table 5).

COS is the presumed to be the most important precursor to background stratospheric aerosol which are primarily sulfate in composition. Hoffman (1990) has shown from satellite measurements that the background aerosol concentration in the stratosphere is increasing at approximately 5 percent per year for the decade from 1980 to 1990. The total COS budget is not very well understood but from Khalil and Rasmussen (1984), biomass burning is not believed to be a large contributor to the total budget. This source is, however presumed to be increasing, particularly over the time period of Hoffman's analysis. Therefore it could play some role in the

Table 5. Comparison of global emissions of sulfur species from biomass burning with emissions from other sources.

Species	Biomass Burning (Tg S/yr)	All sources (Tg S/yr)	Biomass Burning (percent)
Sulfur gases	2.2[a]	105[a]	2
COS	0.09[b]	1.7[a]	5

[a] Bates et al. (1992)
[b] Andreae (1991)

observed stratospheric background aerosol increase. Increasing the background aerosol loading can have significant effect on the energy budget of the planet. It can increase the reflected incoming solar radiation, thus having a net cooling effect.

4.6 Carbonaceous Aerosols

Just as sulfate aerosols have been recognized as the dominant contributor to tropospheric aerosols in industrialized continental areas, Penner et al. (1992) have suggested that smoke aerosols from biomass fires may play a similar role over tropical continental areas. They have proposed an upper limit on the estimate of the global flux of smoke at 3.7×10^{-3} gm^{-2}, or a total of 114 Tg C per year. This corresponds very well with the estimate of Peterson and Junge (1971) of 104 Tg C. Cachier (1993) has suggested that these values may be too high due to the dominant area of savanna fires which has a high proportion of flaming (Ward et al. 1991). Penner et al. (1992) have suggested that as an upper limit this could contribute a -2 W/m^2 cooling when combining the direct and indirect radiative effects of aerosols on the global energy budget. This would represent a near balance between the best estimate of anthropogenic greenhouse warming and aerosol cooling. Cachier (1993) suggests that because of the chemical composition of aerosols, usually consisting of an aggregate of both carbonaceous and sulfate components, further studies of aerosol climate feedback will need to be investigated.

5. Conclusions

Estimates suggest increased biomass burning over the last century (Houghton, 1991), with recent totals ranging from 6000-9000 Tg dry matter per year. Roughly half of that occurs over savanna regions. Carbon released over savanna regions is recycled with little addition to the CO_2 greenhouse. Most of the additional carbon to the atmosphere from biomass burning is due to change in land use, particularly from cleared forest.

Biomass burning is responsible for photochemical production of smog in remote regions that are similar in concentration as those expected in northern hemisphere industrialized/urban regions. The ozone produced from the biomass smog is responsible from ~50 percent of the expected greenhouse warming due to O_3. Biomass burning is also responsible for ~25 percent of the expected greenhouse warming due to CO_2.

Smoke aerosols from biomass burning have been implicated in radiative cooling similar to sulfate aerosols near industrialized continental regions. Smoke aerosols have been proposed to have a combined radiative effect of up to -2 W/m2 (Penner et al. 1992). The increase of aerosols over the last century, partially due to increased biomass burning, may explain why the warming observed is at the lower limit of that predicted by climate models.

The evolution of our planet and ourselves are closely linked with biomass burning. Until recent times it is believed that the natural processes of respiration, photosynthesis and natural fires controlled the concentration of carbon dioxide and most trace gases in our planet's atmosphere. Ice core data shows that CO_2 concentration correlates well with temperature, while increased smoke aerosol concentrations may correspond to climate cooling (Penner et al., 1992). If hydrocarbon tracers in smoke particles from biomass fires can be identified, deposition on polar ice pack may be used along with atmospheric tracer models to constrain recent estimates and historic records of the amount of biomass burned. This in conjunction with model studies will help constraint the amount of trace species emitted from biomass burning. With more refined estimated of biomass burning emissions, additional studies may be performed to determine the magnitudes of natural versus anthropogenic sources of trace species. A first step would be to narrow the uncertainties of the change in the amount of anthropogenic biomass burning practices. This could be done by analysis of smoke aerosol type and concentration deposited in ice cores since the preindustrial times.

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