9

BIOMASS BURNING
AND THE PRODUCTION
OF GREENHOUSE GASES

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1. INTRODUCTION

Biomass burning is a source of greenhouse gases, carbon dioxide, methane, and nitrous oxide. In addition, biomass burning is a source of chemically active gases, including carbon monoxide, nonmethane hydrocarbons, and nitric oxide. These gases, along with methane, lead to the chemical production of tropospheric ozone (another greenhouse gas) as well as control the concentration of the hydroxyl radical, which regulates the lifetime of almost every atmospheric gas. Following biomass burning, biogenic emissions of nitrous oxide, nitric oxide, and methane are significantly enhanced. It is hypothesized that enhanced postburn biogenic emissions of these gases are related to fire-induced changes in soil chemistry and/or microbial ecology. Biomass burning, once believed to be a tropical phenomenon, has been demonstrated by satellite imagery to also be a regular feature of the world's boreal forests. One example of biomass burning is the extensive 1987 fire that destroyed more than 12 million acres of boreal forest in the People's Republic of China and across its border in the Soviet Union. Recent estimates indicate that almost all biomass burning is human-initiated and that it

is increasing with time. With the formation of greenhouse and chemically active gases as direct combustion products and a longer-term enhancement of biogenic emissions of gases, biomass burning may be a significant driver for global change.

The chemistry and climate of our planet are controlled by the presence of trace gases present in very minute quantities-parts per million by volume ppmv = 10^{-6}), parts by billion by volume (ppbv = 10^{-9}), and parts by trillion by volume (pptv = 10^{-12}). Many of these chemistry- and climate-controlling gases are increasing in concentration with time. Atmospheric greenhouse gases, carbon dioxide (CO_2) methane (CH_4), nitrous oxide (N_2O), and tropospheric ozone (O_3) are all increasing with time. Concentrations of chemically active gases, nitric oxide (NO), and carbon monoxide (CO) are also increasing with time. These gases have varied sources of production, including the burning of fossil fuels (source of CO_2, CO, and NO), microbial metabolic activity (CO_2, CH_4, N_2O, and NO), and chemical reactions (O_3). All of these gases are produced directly or indirectly (O_3) by biomass burning. Biomass burning includes the burning of the world's forests and savanna grasslands for land clearing and agricultural use, the burning of agricultural waste and stubble after harvesting, and the burning of biomass for fuel. Global biomass burning is more extensive than previously believed and appears to be increasing with time (Levine, 1990a, 1990b, 1991). It is also thought that the bulk of global biomass burning is human-initiated rather than naturally occurring, such as lightning induced fires (Levine, 1990a, 1990b, 1991). Biomass burning may be an important driver for global change in the atmosphere and climate.

This chapter deals with several aspects of biomass burning and a brief discussion of the gases and particulates produced by the burning oil wells in Kuwait. The first part of the chapter deals with a technique to estimate the instantaneous emissions of trace gases produced by biomass burning using satellite imagery. The second part concerns the recent discovery that burning results in significantly enhanced biogenic emissions of N_2O, NO, and CH_4. Hence, biomass burning has both an immediate and a long-term impact on the production of trace gases to the atmosphere. The objective of this research is to better assess and quantify the role and impact of biomass burning as a driver for global change. It will be demonstrated that satellite imagery of fires may be used to estimate combustion emissions and may in the future be used to estimate the long-term postburn biogenic emissions of trace gases to the atmosphere. The oilfires in Kuwait represent another form of human-initiated burning. The production and emission of atmospheric gases and particulates from these fires will be assessed and compared with similar emissions from global biomass burning.

2. Gaseous Emissions Due to Biomass Burning

Biomass burning includes the combustion of living and dead material in forests, savannas, and agricultural wastes, and the burning of fuel wood. Under the ideal conditions of complete combustion, the burning of biomass material produces carbon dioxide (CO_2) and water vapor (H_2O), according to the reaction

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$
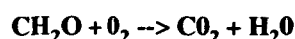
where CH_2O represents the average composition of biomass material. Since complete combustion is not achieved under any conditions of biomass burning, other carbon species, including carbon monoxide (CO), methane (CH_4) nonmethane hydrocarbons (NMHCs), and particulate carbon, result through the incomplete combustion of biomass material. In addition, nitrogen and sulfur species are produced from the combustion of nitrogen and sulfur in the biomass material.

While CO_2 is the overwhelming carbon species produced by biomass burning, its emissions into the atmosphere resulting from the burning of savannas and agricultural wastes are largely balanced by its reincorporation back into biomass via photosynthetic activity within weeks to years after burning. However, CO_2 emissions resulting from the burning of forests converted to nonforested areas and other carbon combustion products from all biomass sources including CH_4, CO, NMHCs, and particulate carbon, are largely "net" fluxes into the atmosphere since these products are not reincorporated into the biosphere.

Biomass material contains about 40% carbon by weight, with the remainder hydrogen (6.7%) and oxygen (53.3%) (Bowen, 1979). Nitrogen accounts for 0.3-3.8%, and sulfur for 0.1-0.9%).9% depending on the nature of the biomass material (Bowen, 1979). The nature and amount of the combustion products depend on the characteristics of both the fire and the biomass material burned. Hot, dry, fires with a good supply of oxygen produce mostly carbon dioxide with little CO, CH_4, and NMHCs. The flaming phase of the fire approximates complete combustion, while the smoldering phase approximates incomplete combustion, resulting in greater production of CO, CH_4, and NMHCs. The percentage production of CO_2, CO, CH_4, NHMCs, and carbon ash during the flaming and smoldering phases of burning based on laboratory studies is summarized in Table 1 (Lobert et al., 1991). Typically for forest fires, the flaming phase lasts on the order of an hour or less, while the smoldering phase may last up to a day or more, depending on the type of fuel, the fuel moisture content, wind velocity, topography, and other param

TABLE 1. Gas Production during Flaming and Smoldering Phases of Burning Based on Laboratory Experiments

	Percentage in Burning Stage (%)	
	Flaming	Smoldering
CO_2	63	37
CO	16	84
CH_4	27	73
NMHCs	33	67
NO_x	66	34
NH_3	15	85
HCN	33	67
CH_3Cl	28	72

Source: Lobert et al. (1991).

eters. For savanna grassland and agricultural waste fires, the flaming phase lasts a few minutes and the smoldering phase lasts up to an hour.

3. EMISSION RATIOS

The total mass of the carbon species (CO_2 + CO + CH_4 + NMHCs + particulate carbon) M(C) is related to the mass of the burned biomass (M) by M(C) = fx M, where f = mass fraction of carbon in the biomass material (40% by weight). To quantify the production of gases other than CO_2, we must determine the emission ratio (ER) for each species. The emission ratio for each species is defined as

$$ER = \frac{\Delta X}{\Delta CO_2}$$

where delta-X is the concentration of the species X produced by biomass burning, delta-X = X* - X, where X* is the measured concentration of X in the biomass burn smoke plume, X is the background (out-of-plume) atmospheric concentration of the species, and delta-CO_2 is the concentration of CO_2 produced by biomass burning, delta-CO_2 = CO_2* - CO_2, where CO_2* is the measured concentration in the biomass burn plume and CO_2 is the background (out of plume) atmospheric concentration of CO_2.

In general, all species emission factors are normalized with respect to CO_2, since the concentrations of CO_2 produced by biomass burning may be directly related to the amount of biomass material burned by simple stoichiometric considerations as discussed earlier. Furthermore, the measurement of CO_2 in

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the background atmosphere and in the smoke plume is a relatively simple and routine measurement.

For the reasons outlined above, it is most convenient to quantify the combustion products of biomass burning in terms of the species emission ratio (ER), that is, the excess species production (above background) normalized with respect to the excess CO_2 production (above background). Measurements of the emission ratio for CH_4, CO, and NMHCs normalized with respect to CO_2 for diverse ecosystems (i.e., wetlands, chaparral, and boreal) for different phases of burning (i.e., flaming and smoldering phases and combined flaming and smoldering phases), called "mixed," are summarized in Table 2.

Some researchers present their biomass burn emission measurements in the ratio of grams of carbon in the gaseous and particle combustion products to the mass of the carbon in the biomass fuel in kilograms. Average emission factors for CO_2, CO, and CH_4 in these units for diverse ecosystems are summarized in Table 3, and emission factors for CO_2, CO, CH_4, NMHCs, and carbon ash in terms of percentage of fuel carbon based on laboratory experiments are summarized in Table 4. Inspection of Tables 2-4 indicates that there is considerable variability in both the emission ratio and emission factor for carbon species as a function of ecosystem burning and the phase of burning (i.e., flaming or smoldering). A recent compilation of CO_2-normalized emission ratios for carbon species is listed in Table 5. This table gives the range for both field measurements and laboratory studies and provides a "best guess."

TABLE 2. Emission Ratios for CO, CH$_4$, and NMHCs for Diverse Ecosystems (in Units of $\Delta X/\Delta CO_2$, in Percent)

	CO	CH$_4$	NMHCs
Wetlands			
Flaming	4.7 ± 0.8	0.27 ± 0.11	0.39 ± 0.17
Mixed	5.0 ± 1.1	0.28 ± 0.13	0.45 ± 0.16
Smoldering	5.4 ± 1.0	0.34 ± 0.12	0.40 ± 0.15
Chaparral			
Flaming	5.7 ± 1.6	0.55 ± 0.23	0.52 ± 0.21
Mixed	5.8 ± 2.4	0.47 ± 0.24	0.46 ± 0.15
Smoldering	8.2 ± 1.4	0.87 ± 0.23	1.17 ± 0.33
Boreal			
Flaming	6.7 ± 1.2	0.46 ± 0.20	0.66 ± 0.26
Mixed	11.5 ± 2.1	1.12 ± 0.31	1.14 ± 0.27
Smoldering	12.1 ± 1.9	1.21 ± 0.32	1.08 ± 0.18

Source: Cofer et al. (1991).

TABLE 3. Average Emission Factors for CO_2, CO, and CH_4 for Diverse Ecosystems (in g Combustion Product C/kg Fuel C)

	CO_2	CO	CH_4
Chaparral 1	1644 ± 44	74 ± 16	2.4 ± 0.15
Chaparral 2	1650 ± 31	75 ± 14	3.6 ± 0.25
Pine, Douglas fir, and brush	1626 ± 39	106 ± 20	3.0 ± 0.8
Douglas fir, true fir, and hemlock	1637 ± 103	89 ± 50	2.6 ± 1.6
Aspen, paper birch, and debris from jack pine	1644 ± 62	82 ± 36	1.9 ± 0.5
Black sage, sumac, and chamise	1748 ± 11	34 ± 6	0.9 ± 0.2
Jack pine, white and black spruce	1508 ± 161	175 ± 91	5.6 ± 1.7
"Chained" and herbicidal paper birch and poplar	1646 ± 50	90 ± 21	4.2 ± 1.3
"Chained" and herbicidal birch, poplar, and mixed hardwoods	1700 ± 82	55 ± 41	3.8 ± 2.8
Debris from hemlock, deciduous and Douglas fir	1600 ± 70	83 ± 37	3.5 ± 1.9
Overall average	1650 ± 29	83 ± 16	3.2 ± 0.5

Source: Radke et al. (1991).

TABLE 4. Emission Factors for Gases and Ash Based on Laboratory Experiments (in % of Fuel Carbon and Fuel Nitrogen)

	Mean	Range
CO_2	82.58	49.17–98.95
CO	5.73	2.83–11.19
CH_4	0.424	0.14–0.94
NMHC (as C)	1.18	0.14–3.19
Ash (as C)	5.00	0.66–22.28
Total sum C	94.91	—
N_2	21.60	—
NO_x	13.55	5.27–21.69
NH_3	4.15	1.04–11.74
HCN	2.64	0.31–6.75
CH_3CN	1.00	0.079–2.323
Nitrates	1.10	—
Ash (as N)	9.94	1.75–45.98
Total sum N	53.98	—

Source: Lobert et al. (1991).

TABLE 5. CO_2-Normalized Emission Ratios for Combustion Species: Summary of Field Measurements and Laboratory Studies (in g Species/kg C in CO_2)

	Field Measurements	Laboratory Studies	"Best Guess"
CO	6.5–140	59–105	100
CH_4	6.2–16	11–16	11
NMHCs	6.6–11.0	3.4–6.8	7
Particulate organic carbon (including elemental carbon)	7.9–54	—	20
Elemental carbon (black soot)	2.2–16	—	5.4
NO_x	2–8	0.7–1.6	2.1
NH_3	0.9–1.9	0.08–2.5	1.3
N_2O	0.18–2.2	0.01–0.05	0.1
H_2	33	—	33
SO_x	0.1–0.34	—	0.3
COS	0.005–0.016	—	0.01
CH_3Cl	0.023–0.033	0.02–0.3	0.05
O_3	4.8–40	—	30

Source: Andreae (1991).

Once the mass of the burned biomass (M) and the species emission ratios (ER) are known, the gaseous and particulate species produced by biomass burn combustion may be calculated. The mass of the burned biomass (M) is related to the area (A) burned in a particular ecosystem by the following relationship (Seiler and Crutzen, 1980):

$$M = A \times B \times \alpha \times \beta$$

where "beta" is the average biomass material per unit area in the particular ecosystem (g/m^2), "alpha" is the fraction of the average above-ground biomass relative to the total average biomass B, and "beta" is the burning efficiency of the above-ground biomass. Parameters B, "alpha", and "beta" vary with the particular ecosystem under study and are determined by assessing the total biomass before and after burning.

The total area burned during a fire may be assessed using satellite data. Recent reviews have considered the extent and geographical distribution of biomass burning from a variety of space platforms: astronaut photography (Wood and Nelson, 1991), the NOAA (National Oceanic and Atmospheric Administration) polar orbiting Advanced Very High Resolution Radiometer

(AVHRR) (Brustet et al., 1991a, 1991b; Cahoon et al., 1991; Robinson, 1991a, 1991b), the Geostationary Operational Environmental Satellite (GOES) Visible Infrared Spin Scan Radiometer Atmospheric Sounder (VAS) (Menzel et al., 1991), and the Landsat Thematic Mapper (TM) (Brustet et al., 1991b).

Hence, the contribution of biomass burning to the total global budget of any atmospheric species depends on a variety of ecosystem and fire parameters, including the particular ecosystem that is burning (which determines the parameters B, "alpha", and "beta"), the mass consumed during burning, the nature of combustion (complete vs. incomplete), the phase of combustion (flaming vs. smoldering), and knowledge of how the species emission factors (EF), vary with changing fire conditions in various ecosystems. The contribution of biomass burning to the global budgets of any particular species depends on precise knowledge of all these parameters. While all these parameters are known imprecisely, the largest uncertainty is probably associated with the total mass (M) consumed during biomass burning on an annual basis (and there are large year-to-year variations in this parameter!). The total mass of burned biomass material on an annual basis according to source of burning is summarized in Table 6 (Seiler and Crutzen, 1980; Crut zen and Andreae, 1990; Hao et al., 1990; Andreae, 1991). The estimate for carbon released of 3940 Tg/year includes all carbon species produced by biomass combustion (CO_2 + CO + CH_4 + NMHCs + particulate carbon). About 90% of the released carbon is in the form of CO_2 (about 3550 Tg/year).

TABLE 6. Global Estimates of Annual Amount of Biomass Burning and the Resulting Release of Carbon and CO_2 to the Atmosphere

Source of Burning	Biomass Burned (Tg/year)[a]	Carbon Released (Tg(C)/year)[b]	CO_2 Released (Tg(C)/year)[c]
Savanna	3690	1660	1494
Agricultural waste	2020	910	819
Fuel wood	1430	640	576
Tropical forests	1260	570	513
Temperature and boreal forests	280	130	117
Charcoal	21	30	27
World total	8700	3940	3546

[a] 1 Tg (teragram) = 10^6 metric tons = 10^{12} g.

[b] Based on a carbon content of 45% in the biomass material. In the case of charcoal, the rate of burning has been multiplied by 1.4.

[c] Assuming that 90% of the carbon released is in the form of CO_2.

Sources: Seiler and Crutzen (1980), Crutzen and Andreae (1990), Hao et al. (1990), Andreae (1991).

5. HISTORIC CHANGES IN BIOMASS BURNING

It is generally accepted that the emissions from biomass burning have increased in recent decades, largely as a result of increasing rates of deforestation in the tropics. Houghton (1991) estimates that gaseous and particulate emissions to the atmosphere due to deforestation have increased by a factor of 3-6 over the last 135 years. He also believes that the burning of grasslands, savannas, and agricultural lands has increased over the last century because rarely burned ecosystems, such as forests, have been converted to frequently burned ecosystems, such as grasslands, savannas, and agricultural lands. In Latin America, the area of grasslands, pastures, and agricultural lands increased by about 50% between 1850 and 1985. The same trend is true for South and Southeast Asia. In summary, Houghton (1991) estimates that total biomass burning may have increased by about 50% since 1850. Most of the increase results from the ever-increasing rates of forest burning, with other contributions of burning (grasslands, savannas, and agricultural lands) having increased by 15-40%. The increase in biomass burning is not limited to the tropics. In analyzing 50 years of fire data from the boreal forests of Canada, Russia and other former Soviet countries, the Scandinavian countries, and Alaska, Stocks (1991) has reported a dramatic increase in area burned in the 1980s. The largest fire in the recent past destroyed more than 12 million acres of boreal forest in the People's Republic of China and Russia in a period of less than a month in May 1987 (Cahoon et al., 1991).

The historic data indicate that biomass burning has increased with time and that the production of greenhouse gases from biomass burning has increased with time. Furthermore, the bulk of biomass burning is human-initiated. As greenhouse gases build up in the atmosphere and the Earth becomes warmer, there may be an enhanced frequency of fires. The enhanced frequency of fires may prove to be an important positive feedback on a warming Earth. However, the bulk of biomass burning worldwide may be significantly reduced. Policy options for mitigating biomass burning have been developed (Andrasko et al., 1991). For mitigating burning in the tropical forests, where much of the burning is aimed at land clearing and conversion to agricultural lands, policy options include the marketing of timber as a resource and improved productivity of existing agricultural lands to reduce the need for conversions of forests to agricultural lands. Improved productivity will result from the application of new agricultural techn ology (fertilizers, etc.). For mitigating burning in tropical savanna grasslands, animal grazing could be replaced by stall feeding since savanna burning results from the need to replace nutrient-poor tall grass with nutrient-rich short grass. For mitigating burning of agricultural lands and croplands,

incorporate crop wastes into the soil, instead of burning, as is the present practice throughout the world. The crop wastes could also be used as fuel for household heating and cooking rather than cutting down and destroying forests for fuel as is presently done.

6. THE GREAT CHINESE~OVIET FIRES OF 1987

On May 6, 1987, three fires resulting from human activities began in the extensive boreal forest of the Helongjing Province of the People's Republic of China. The Helongjing Province borders the former Soviet Union along the Amur River. The Helongjing Province fires combined and continued to burn for about 3 weeks. More than 40,000 Chinese firefighters were called in to battle the fire. During the time that the Chinese fire was spreading, fire activity began across the Amur River in the Soviet Union. The exact cause of the fires in the Soviet Union is not known, but the possibility exists that they were related to the Chinese fires. The fires in

China and the Soviet Union in May 1987 were very large events, perhaps the largest fires recorded in each country. Collectively, they may have been the largest fires recorded in history. These fires are referred to as either "The Great Chinese Fire of 1987" or "The Great Chinese/Soviet Fire of 1987." Because of the very large area and mass of boreal forest destroyed b y this event, it was decided to study this fire using satellite imagery and to estimate the gaseous emissions released to the atmosphere by the fire. The areal extent of biomass burning by the ecosystem, which is deduced from satellite imagery, provides an indication of the total amount of dry biomass burned within that ecosystem per unit time.

Using images obtained by the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA-9 meteorological satellite, Cahoon et al. (1991) have estimated the areal extent of the 1987 fires in the boreal forests of China and the former Soviet Union. Cahoon et al. (1991) estimate the fire covered at least 2.5 million acres in China and about 10 million acres in the Soviet Union during its 21-day lifetime in May 1987. Hence, the fires covered at least 12 million acres or 4.86×10^{10} m^2. According to Seiler and Crutzen (1980), the following numerical parameters are characteristic of a boreal forest: $B = 25 \times 10^3$ g/m^2, "alpha" = 75%, and "beta" = 20%. Using these parameters with the satellite-determined estimate for the total area of the fire, we find $M = 1.8 \times 10^{14}$ g and $M(CO_2)$ = $0.45M$ = 8.1×10^{13} g C. Cofer et al. (1990) have measured gaseous emissions from boreal forest fires and determined the emission ratios for boreal forest fires to be CO/CO_2 = 12.3%, CH_4/CO_2 = 1.26%, and $NHMCs/CO_2$ = 1.03%. Using these emis sions ratios, we calculate the gaseous carbon emissions from the Chinese-Soviet fire during its 21-day

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lifetime to be CO_2: 7.1×10^{13} g C, CO: 8.6×10^{12} g C; CH_4: 8.8×10^{11} g C and NHMCs: 7.2×10^{11} g C.

The calculation of gaseous emissions from the Chinese-Soviet fire of 1987 clearly illustrates that satellite imagery of fires may be used to determine gaseous emissions. To utilize this technique, we must know certain ecosystem-dependent parameters (i.e., B, "alpha", "beta") and the emission ratio for each gas under consideration. However, once these parameters are known for each of the world's major ecosystems, satellite imagery of fires will provide important information on gaseous emissions from these fires. The planned NASA Earth Observing System (EOS) will provide a unique platform for the routine global monitoring of burning and may provide definite information on the role of global burning as a source of trace gases to the atmosphere.

7. MICROBIAL BIOGENIC EMISSIONS

Microbial metabolic activity in the soils and wetlands of the world is a significant global source of trace gases to the atmosphere (Levine, 1989). Nitrifying and denitrifying microorganisms utilize ammonium and nitrate in soil to produce biogenic emissions of nitrous oxide and nitric oxide and methanogenic microorganisms in wetlands, swamps, and rice paddies utilize carbon dioxide, acetate, and formate to produce biogenic emissions of methane. Biogenic emissions of N_2O, NO, and CH_4 due to microbial metabolic processes are very significant sources of these gases to the global atmosphere. Recent measurements indicate that burning results in significantly enhanced emissions of all three gases.

7.1. Biogenic Emissions of N_2O and NO

Measurement of biogenic emissions of NO and N_2O were obtained before and after two prescribed fires occurring in the San Dimas Experimental Forest, a chaparral ecosystem located in the Angeles National Forest, San Gabriel Mountains, about 60 km northeast of Los Angeles, California (Anderson et al., 1988; Levine et al., 1988). These controlled fires were planned and implemented by the Los Angeles County Fire Department as part of their fire management and controlled burn activities at the San Dimas Experimental Forest. All flux measurements reported in this chapter were obtained using the flux chamber method. This technique and the detection instrumentation and calibration methods are discussed in detail elsewhere (Anderson et al., 1988; Levine et al., 1988, 1990). Our measurements indicate that NO and N_2O soil emissions from wetted sites exceeded those from dry sites and that the burned sites had significantly enhanced emissions. Wetting stimulates the

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metabolic activity of soil microorganisms and hence leads to the metabolic production of NO and N_2O. The artificial wetting performed in these experiments simulated natural wetting due to rainfall: 1 gal (3.8 liters) of water was applied to the 0.4-m^2 area of the flux chamber. NO emissions from burned and wetted sites reached 60 ng N m^{-2} s^{-1}, which exceeded NO fluxes from agricultural fields measured after the application of fertilizers (Anderson et al., 1988). Comparable increases in NO emissions after burning were found in the tropical savanna of Venezuela (Johansson et al., 1988). N_2O emissions from burned and wetted sites also approached 60 ng N M^{-2} s^{-1}. N_2O emissions from unburned and wetted sites were below the detection limit of the measurement (2 ng N m^{-2} s^{-1}) On the three occasions that N_2O emissions were detectable (from the three burned and wetted sites), the ratio of the NO emissions to the N_2O emissions ranged from about 2.7-3.4. This observation may shed some light on the process responsible for the enhanced postfire

emissions of both NO and N_2O as discussed later.

Over the years, researchers at the San Dimas Experimental Forest have measured the concentrations of ammonium (NH_4^+) and nitrate (NO_3^-) in the soil of the chaparral forest before and after prescribed burns (DeBano et al., 1979; Dunn et al., 1979). DeBano et al. (1979) concluded that burning significantly increases the concentration of ammonium and decreases the concentration of nitrate in the soil. DeBano et al. (1979) found that immediately after an intense fire, soil associated with chamise vegetation increased in ammonium concentration from 3.79 to 10.77 kg/ha and the nitrate concentration decreased from 0.58 to 0.47 kg/ha. They also found that immediately after an intense fire, the soil associated with Ceanothus vegetation increased in ammonium concentration from 1.69 to 12.13 kg/ha and the nitrate concentration decreased from 1.05 to 0.33 kg/ha (DeBano et al., 1979).

In summary, we found that NO emissions from moderately or heavily burned and wetted grass and vegetated sites reached 60 ng N $m^{-2} s^{-1}$. These fluxes exceeded NO fluxes measured from a fertilized cornfield within days after fertilization and greatly exceeded NO fluxes from natural (unfertilized) grasses (Anderson and Levine, 1987). N_2O emissions from lightly, moderately, and heavily burned and wetted sites were also significantly enhanced. N_2O fluxes were not detected from these sites prior to the burn even after wetting (indicating an N_2O flux of less than 2 ng N $m^{-2} s^{-1}$) From burned and wetted sites, the flux of NO exceeded the N_2O flux by factors ranging from 2.7 to 3.4. Preburn and postburn measurements of soil ammonium and nitrate (DeBano et al., 1979) and laboratory studies of biogenic emissions of nitric oxide and nitrous oxide (Anderson and Levine, 1986) have provided important information on the microorganism and the metabolic pathway responsible for the postburn enhancement in nitric oxide and nitrous oxide. Laboratory studies showed that over a wide range of oxygen levels (0-20%), the

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ratio of NO to N_2O emissions for nitrifying bacteria ranged from about 1.0 to 8.5, while that ratio for denitrifying bacteria was less than unity (Anderson and Levine, 1986). This observation coupled with the measurements that show soil ammonium, the substrate for nitrification, increased after burning, while soil nitrate, the substrate for denitrification, decreased after burning (DeBano et al., 1979), suggests that the postburn enhanced emissions of nitric oxide and nitrous oxide most probably resulted from nitrification associated with enhanced postburn concentrations of Soil ammonium.

7.2. Biogenic Emissions of CH4

Our group obtained measurements of biogenic emissions of CH_4 before and after two prescribed wetlands fires at the NASA John F. Kennedy Space Center (KSC) within the Merrit Island National Wildlife Refuge in Brevard County, Florida (Levine et al., 1990). These controlled fires, planned and implemented by the U.S. Fish and Wildlife Services as part of their fire management and controlled burn activities at KSC, occurred on November 9, 1987 (KSC I), and on November 11, 1988 (KSC III). During these burns we obtained prefire and posifire measurements of CH_4 emissions from two different wetlands sites, a *Juncus roemerianus* marsh and *Spartina bakeri* marsh with standing water.

Preburn and postburn measurements of biogenic emissions of methane were obtained at two different standing water sites (a *J. roemerianus* marsh and a *S. bakeri* marsh) at both the November 9, 1987 (KSI I) and November 11, 1988 (KSC III) fires. The methane emissions increased significantly following the 1987 and 1988 fires. In both measurement sets the preburn and postburn emissions form the *S. bakeri* sites exceeded the emissions from the *J. roemerianus* sites. However, the magnitude of the methane emissions from both sites in 1987 was less than the magnitude of the emissions from both sites in 1988. We believe that the explanation for the lower methane emissions and the higher values of pH in 1987 is due to the fact that only 6 days before the 1987 fire (November 9, 1987), both the *J. roemerianus* and *S. bakeri* marshes were very dry, that is, not covered with any standing water. On November 3, 1987, a late-season tropical depression produced 14.5 cm of rain in a 24-hour period. This storm provided enough rain for the marsh to be covered with standing water less than a week before the fire. In direct contrast, for the 1988 measurements, both marsh sites were flooded and continuously covered with standing water (about 18 cm) since August, about three months before the November 11, 1988 fire. We believe that the lowervalued methane emissions recorded in 1987, compared to 1988, were due to the fact that the marshes, because of the very recent rain and standing water, had not yet reached equilibrium as an anaerobic environment. The higher

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values of pH for the standing water in 1987 is also attributed to the fact that very recent rains were responsible for the standing water.

After the 1987 fire, methane emissions in the *Juncus roemerianus* marsh increased from below the detection limit of the instrument (0.3 x 10^{-3} g $CH_4 m^{-2}$ day^{-1}) to 5-6 x 10^{-3} g CH_4 m^{-2} day^{-1}. Measurements of methane emissions at our unburned, control *J. roemerianus* site were always below the detection limit of the instrument. Methane emissions in the *S. bakeri* site, which were below

the detection limit of the instrument before the fire, increased to 34.5 x 10^{-3} g CH_4 m^{-2} day^{-1} after the fire. Measurements of methane emissions before and after the November 11, 1988 fire in both *J. roemerianus* and *S. bakeri* marshes showed a very similar trend. The main difference is that in the 1988 measurements, methane emissions were detected before the fire. We attribute the detectability of the methane emissions before the 1988 fire to the fact that standing water covered both marshes for at least 3 months prior to the start of the measurements, thereby establishing the anaerobic environment needed for the production of methane.

Both of these marsh sites were covered with about 18 cm of standing water for at least 3 months before the fire. The CH_4 emission histories from both sites following the fire are similar. Three days following the fire the methane emissions from both sites were somewhat below the prefire level. Five days after the fire the *J. roemerianus* site exhibited its maximum flux (about 100% above the prefire value), and 3 days after the fire the *S. bakeri* site exhibited its maximum flux (about 50% above the prefire value). We believe that the decrease in methane emissions within 48 h of the fire is due to large quantities of methane purged from the marsh water due to the high temperature of the fire as well as due to the removal of methane-saturated flora, which serve as a conduit for methane emissions (Sebacher et al., 1985).

Methane emissions from different wetlands ecosystems are summarized in Table 7. Note that only two ecosystems, high-latitude, peat-rich terrain and Alaskan alpine fen produced methane emissions that exceeded the maximum postburn emissions measured after the 1988 fire.

After the short-lived postburn decrease in methane emissions in 1988 the emissions began to increase, as they did in 1987. Methane is produced by the metabolic activity of methanogenic bacteria in a strictly anaerobic environment. Methanogens can only utilize a restricted suite of compounds for both growth and the metabolic production of methane. Compounds utilized by methanogens for growth and methane production include carbon dioxide, acetate, formate, methanol, and methylated amines (Cicerone and Oremland, 1988). Carbon dioxide acetate and formate are produced in large concentrations during biomass burning. Carbon dioxide is the most abundant gas produced during biomass burning (Cofer et al., 1990). Our chemical analyses of biomass burn particulates collected by airborne filters in the smoke

TABLE 7. Methane Emissions from Different Wetland Ecosystems

Ecosystems	CH_4 Emissions (g CH_4 m^{-2} day^{-1})
High-latitude, peat-rich ecosystems (Svensson, 1980)	0.3
Alaskan alpine fen (Sebacher et al., 1986)	>0.250
Maximum postburn emission (Levine et al., 1990)	0.176
Preburn emission range (Levine et al., 1990)	0.025–0.146
Alaskan wetland ecosystems (Sebacher et al., 1986)	0.112
Sawgrass (Bartlett et al., 1985)	0.11
Swamp forest (Bartlett et al., 1985)	0.072
Florida Everglades (Bartlett et al., 1985)	0.013–0.03
Forested freshwater swamps, southeastern United States (Harriss and Sebacher, 1981)	0.0046–0.068
Great Dismal Swamp (Harriss et al., 1982)	<0.001

Source: Levine et al. (1990).

plume indicate that these particulates contain large concentrations of both acetate and formate. Carbon dioxide is a very water-soluble gas and acetate and formate are very water-soluble compounds. In general, methanogens are dependent on other microorganisms for providing them with the needed carbon dioxide, acetate, and formate (Cicerone and Oremland, 1988). However, biomass burn combustion products are a significant source of the substrates needed by methanogens for the production of methane. Hence we hypothesize that the postburn enhancement of methane emissions is related to the enhanced concentrations of carbon dioxide, acetate, and formate supplied to the methanogens by biomass burning. The carbon dioxide, acetate, and formate are dissolved into the marsh standing water and diffuse down to the marsh floor, where they are utilized by the methanogens in the production of methane. The acetate and formate rich ash particles began falling to the marsh as soon as the fire began. We estimate that these partic les diffused through the marsh standing water in only a matter of hours. It is possible that the postburn enhancement of methane emissions is also related to the massive destruction of marsh flora by the fire and the elimination of a user of nutrients, making more nutrients available to the marsh methanogenic bacteria.

Measurements of preburn and postburn biogenic emissions of methane from a wetlands indicate a significant posthurn emission enhancement. We hypothesize that the postburn enhancement in methane is due to enhanced levels of carbon dioxide, formate, and acetate, all water-soluble biomass burn combustion products, that readily dissolve into the standing water of the wetlands marsh and serve as the substrate for the production of methane by

methanogenic bacteria. These measurements indicate for the first time that burning results in enhanced biogenic emissions of methane in the wetlands.

8. BIOMASS BURNING: A GLOBAL PHENOMENON

Recent estimates suggest that global burning is much more widespread and may cover 300-700 million ha (3-7 million km^2) per year (National Academy of Sciences, 1984), which corresponds to 2-5% of the land area of our planet (1 hectare, ha = 2.47 acres). Much of this burning is human initiated and appears to be increasing with time (Levine, 1990a, 1990b). When we think of human-initiated burning, we usually think of only the burning of the tropicai rain forest and the tropical savanna for land clearing. In Brazil alone, about 8 million ha of tropical rain forest were burned for land clearing in 1987 (Booth, 1989). Brazil possesses 137 million ha of tropical forest, which is 30% of the world's total and 3 times as much as Indonesia, which is second to Brazil in its tropical forest extent (Booth, 1989). However, the burning of living and dead biomass for land clearing is not restricted to the tropics. For 9 out of 10 world regions there has been a significant transformation of natural forests and woodlands to grasslands, pasture, and croplands via burning for the period 1850 to 1980 (International Institute for Environment and Development and World Resources Institute, 1987). According to this study, the forests and woodlands area for each of the 10 world regions changed by the indicated amount from 1850 to 1980: Latin America, from 1420 to 1151 million ha, a decrease of 19%; tropical Mrica, from 1336 to 1074 million ha, a decrease of 20%; former Soviet Union, from 1067 to 941 million ha, a decrease of 12%; North America, from 971 to 942 million ha, a decrease of 3%; South Asia, from 317 to 180 million ha, a decrease of 43%; Pacific developed countries, from 267 to 246 million ha, a decrease of 8%; Southeast Asia, from 252 to 235 million ha, a decrease of 7%; Europe, from 159 to 167 million ha, an increase of 4%; China, from 96 to 58 million ha, a decrease of 39%; North Mrica and the Middle East, from 34 to 14 million ha, a decrease of 60%. By combining all 10 world regions, we find that the total area of forests and woodlands has changed from 5919 to 5007 million ha from 1850 to 1980, a decrease of 15%. It is interesting to note that several regions that have experienced the greatest loss of forests and woodlands are extratropical: the former Soviet Union, North America, and China. In fact, two very large recent fires occurred in the temperate and boreal forests. In the autumn of 1988, nearly 0.6 million ha of Yellowstone National Park burned (Jeffrey, 1989). These fires covered two-thirds of the 0.9 million ha of Yellowstone, the world's largest temperate forest. Mtogether in the h9t and dry summer and autumn of 1988, 1.5 million ha in the western United States and 0.8

million ha in Alaska burned (Jeffrey, 1989). However, these fires were dwarfed by fires in China and the Soviet Union a year earlier in what may have been the largest fires ever recorded, as described in this chapter. These statistics indicate that fires, mostly human-initiated, have transformed a significant amount of forests and woodlands into grasslands, pasture, and croplands over the last 130 years, and that these fires are not limited to the tropics (Levine, 1990a, 1990b, 1991).

The burning of the world's forests, grasslands, and agricultural stubble has several distinct impacts on the atmosphere and climate. Burning leads to the production of the atmospheric greenhouse gases carbon dioxide, methane, and tropospheric ozone. Burning also leads to the atmosphere buildup of carbon monoxide and nitric oxide, which forms nitric acid, the fastest growing component of acid rain. Estimates of the atmospheric gases and particulates produced by global biomass burning are given in Table 8 (Levine, 1990a). Burning of the world's forests destroys a major sink for atmospheric carbon dioxide and an important source of atmospheric oxygen due to photosynthetic activity. Burning also enhances the biogenic production of greenhouse gases, nitrous oxide, and methane and nitric oxide, the precursor of nitric acid. Global burning has significantly increased over the last century with the bulk of it human-initiated (Levine, 1990a, 1990b, 1991). The countries of the world must reexamine their biomass burning practices with the goal of a significant reduction. The role of human-initiated biomass burning as a driver of global atmospheric change must be reduced.

TABLE 8. Estimates of Global Emissions from Biomass Burning and Global Emissions from All Sources

	Biomass Burning (Tg Element/Year)	All Sources (Tg Element/Year)	Biomass Burning (%)
CO_2	3500	8700	40
O_3[a]	420	1100	38
CO	350	1100	32
H_2	19	75	25
NMHC	24	100	24
CH_3Cl	0.51	2.3	22
NO_x	8.5	40	21
NH_3	5.3	44	12
CH_4	38	380	10
Elemental carbon	19	22	86
Particulate organic carbon	69	180	39
Total particulate matter	140	1530	7

[a] O_3 is not a direct combustion product of biomass burning but results from photochemical reactions involving CO, NMHC, and NO_x.
Source: Levine (1990a).

9. BURNING OIL WELLS IN KUWMT AND PRODUCTION OF ATMOSPHERIC GASES AND P~CUIATES

The opening sentences of the Executive Summary of the World Meteorological Organization (1991) report on the Kuwait oilfield fires state: "The world is facing a unique, man-caused environmental pollution on an order never before experienced. The 500 or more burning oil wells in the Kuwaiti oilfields and the oil released on land and in the Gulf represent unprecedented threat to the environment." As much as 5-6 million barrels of crude oil were burning each day (Horgan, 1991; World Meteorological Organization, 1991). According to the World Meteorological Organization (1991) report, one of the key questions that as yet remains unanswered is: "What is the compoSition and amount of gaseous and particulate by-products being produced from the burning oil wells?" Calculations performed by this author to address this question are summarized on Tables 9 and 10. According to these calculations, the Kuwaiti oil fires will increase the global annual emissions of CO_2 and CO by about 3% each. This is a relatively small contr ibution compared to the contribution of these gases by global biomass burning: about 40% for CO_2 and 32% for CO (Levine, 1990a). The real impact of the Kuwaiti oilfires will be felt on the regional and local scales, where levels of CO_2, CO, SO_2, and atmospheric particulates (soot) are extremely high. High levels of atmo-

TABLE 9. Estimate of Gases and Particulates Produced by Kuwaiti Oilfires

Rate of burning oil = 6 million barrels per day
    1 barrel = 42 gallons
    1 gallon = 7.3 pounds

Rate of burning oil = 920,000 tons per day
  Carbon content of oil = 87%
  Sulfur content of oil = 1%
  CO_2 = 90% of carbon combustion
  CO = 10% of carbon combustion
  1 ton of carbon = 3.7 tons of CO_2
  1 ton of carbon = 2.3 tons of CO
  1 ton of sulfur = 3.0 tons of SO_2
  1 ton of carbon = 3.0×10^{-2} C tons of particulates

Emissions per Day
  CO_2 = 2.66 million tons of CO_2
  CO = 184,000 tons of CO
  SO_2 = 27,600 tons of SO_2
  Particulates = 24,000 tons of C particulates

TABLE 10. Estimate of Gases and Particulates Produced by Kuwaiti Oilfires and Comparison with all Global Sources

	Emissions per Year (Metric Tons)[a]		
	Kuwaiti Oilfires	Global[b] (All Sources)	Kuwait (%)
CO_2	970×10^6 CO_2 = 262×10^6 C	8700×10^6 C	3
CO	67×10^6 CO = 29.2×10^6 C	1100×10^6 C	3
SO_2	10×10^6 SO_2 = 3.3×10^6 S	150×10^6 S	2
Particulates	8.8×10^6	1530×10 C	0.5

[a] 1 metric ton = 10^6 g, 1 Tg = 10^{12} g = 10^6 metric tons.
[b] Levine, J. S., 1990. EOS 71, 1075–1077.

spheric particulates in the <u>troposphere</u> have resulted in local and regional scale cooling due to the absorption and scattering of incoming solar <u>radiation</u>. High levels of these particulates and gases are detrimental to human health.

REFERENCES

Anderson, I. C. and J. S. Levine, 1986. Relative rates of nitric oxide and nitrous oxide production by nitriflers, denitriflers, denitrifiers, and nitrate respirers. *Appl. Environ. Microbiol* 51, 938-945.

Anderson, I. C., J. S. Levine, M. A. Poth, and P.1. Riggan, 1988. Enhanced biogenic emissions of nitric oxide and nitrous oxide following surface biomass burning. *J. Geophys. Res.* 93, 3893-3898.

Andrasko, K. 1., D. R. Ahuja, S. M. Winnett, and D. A. Tirpak, 1991. Policy options for managing biomass burning to mitigate global climate change. In 1. S. Levine (ed.), *Global Biomass Burning: Atmospheric Climatic, and Biospheric Implications*. MIT Press, Cambridge, Massachusetts, pp. 445-456.

Andreae, M. 0., 1991. Biomass burning. Its history, use, and distribution and its impact on environmental quality and global climate. In J.S. Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Massachusetts, pp. 3-21.

Arkin, H. and R. R. Colton, 1953. *Statistical Methods*. Barnes and Noble, New York.

Bartlett, K. B., R. C. Rarriss, and D. I. Sebacher, 1985. Methane flux from coastal salt marshes. *J. Geophys. Res.* 90, 5710-5720.

Booth, W., 1989. Monitoring the fate of the forests from space. *Science* 243, 142~1429.

Bowen, H. 1. M., 1979. *Environmental Chemistry of the Elements*. Academic Press, London.

Brustet, 1. M., 1. B. Vickos, 1. Fontan, K. Manissadjan, A. Podaire, and F. Lavenue, 1991a. Remote sensing of biomass burning in West Africa with NOAA-AVHRR. In J.S. Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp.47-52.

Brustet, J. M., J. B. Vickos, J. Fontan, A. Podaire, and F. Lavenue, 1991b. Characterization of active fires in West African savannas by analysis of satellite data: Landsat thematic mapper. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp. 53-60.

Cahoon, D. R., Jr., J. S. Levine, W. R. Cofer III, J. E. Miller, G.M. Tennille, T. W. Yip, and B. J. Stocks, 1991. The great Chinese fire of 1987: A view from space. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass.

Cicerone, R. J. and R. S. Oremland, 1988. Biogeochemical aspects of atmospheric methane. *Global Biogeochem. Cycles* 2, 299-327.

Cofer, W. R. III, J. S. Levine, E. L. Winstead, and B. J. Stocks, 1990. Gaseous emissions from Canadian boreal forest fires. *Atmos. Environ.* 24A, 1653-1659.

Cofer, W. R. III, J. S. Levine, E. L. Winstead, and B. J. Stocks, 1991. Trace gas and particulate emissions from biomass burning in temperate ecosystems. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implication*. MIT Press, Cambridge, Mass., pp. 203-208.

Crutzen, P. J. and M. 0. Andreae, 1990. Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* 250, 1669-1678.

DeBano, L. F., G. F. Eberlein, and P. H. Dunn, 1979. Effects of burning on chaparral soils, I, Soil nitrogen. *Soil Sci. Soc. Am. J.* 43, 504-509.

Dunn, P. H., L. F. DeBano, and G.E. Eberlein, 1979. Effects of burning on chaparral soils: II. Soils microbes and nitrogen mineralization. *Soil Sci. Am. J.* 43, 509-514.

Hao, W. M., M. H. Liu, and P. J. Crutzen, 1990. Estimates of annual and regional release of CO_2 and other trace gases to the atmosphere from fires in the tropics, based on FAO statistics for the period 1975-1980. In J. G. Goldammer (ed.), *Fire in the Tropical Biota: Ecosystem Processes and Global Changes*. Springer-Verlag, Berlin-Heidelberg, pp. 440-462.

Harriss, R. C. and D. I. Sebacher, 1981. Methane flux in forested freshwater swamps of the southeastern United States. *Geophys. Res. Lett.* 8, 1002-1004.

Harriss, R. C., D. I. Sebacher, and F. P. Day, Jr., 1982. Methane flux in the Great Dismal Swamp. *Nature* 297, 673-674.

Horgan, J., 1991. Up in flames: Kuwait's burning oil wells are a sad test of theories. *Sci. Am.* 265, 17-24 (May 1991).

Houghton, R. A., 1991. Biomass burning from the perspective of the global carbon cycle. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp.321-325.

International Institute for Environment and Development and World Resources Institute. 1987. *World Resources 1987*, Basic Books, New York.

Jeffrey, D., 1989. Yellowstone: The great fires of 1988. *Natl. Geogr.* 175, 255-273.

Johansson, C., H. Rodhe, and E. Sanhueza, 1988. Emission of NO in a tropical savanna and a cloud forest during the dry season. *J. Geophys. Res.* 93, 7180-7192.

Levine, J. S., 1989. Photochemistry of biogenic gases. In M. B. Rambler, L. Margulis, and R. Fester (eds.), *Global Ecology: Towards a Science of the Biosphere*. Academic, San Diego, Calif., pp.51-74.

Levine, J. S., 1990a. Global biomass burning: Atmospheric, climatic and biospheric implications. *EOS, Transactions, American Geophysical Union* 71, 1075-1077.

Levine, J. S., 1990b. Atmospheric trace gases: Burning trees and bridges. *Nature* 346, 511-512.

Levine, J. S., 1991. *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass.

Levine, J. S., W. R. Cofer, D. I. Sebacher, E. L. Winstead, S. Sebacher, and P. J. Boston, 1988. The effects of fire on biogenic soil emissions of nitric oxide and nitrous oxide. *Global Biogeochem. Cycles.* 3, 445-449.

Levine, J. S., W. R. Cofer, D. I. Sebacher, P. P. Rhinehart, F. L. Winstead, S. Sebacher, C. R. Hinkle, P. A. Schmalzer, and A. M. Koller, Jr., 1990. The effects of fire on biogenic emissions of methane and nitric oxide from wetlands. *J. Geophys. Res.* 95, 1853-1864.

Lobert, J. M., D. H. Scharffe, W. M. Hao, T. A. Kuhlbusch, R.Seuwen, P. Warnesk, and P. J. Crutzen, 1991. Experimental evaluation of biomass burning emissions: Nitrogen and carbon containing compounds. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp.289-304.

Menzel, W. P., E. C. Cutrim, and E. M. Prins, 1991. Geostationary satellite estimation of biomass burning in Amazonia during BASE-A. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp. 41~6.

National Academy of Sciences, 1984. *Global Tropospheric Chemistry: A Plan for Action*. National Academy Press, Washington, D.C.

Radke, L. F., D. A. Hegg, P. V. Hobbs, J. D. Nance, J. H. Lyons, K. K. Laursen, R. F. Weiss, P. J. Riggan, and D. E. Ward, 1991. Particulate and trace gas emissions from large biomass fires in North America. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp.209-224.

Robinson, J. M., 1991a. On uncertainty in the computation of global emissions from biomass burning. *Internatl. J. Remote Sensing* 12, 3-24.

Robinson, J. M., 1991b. Problems in global fire evaluation: Is remote sensing the solution? In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp. 67-73.

Sebacher, D. I., R. C. Harriss, and K. B. Bartlett, 1985. Methane emissions to the atmosphere through aquatic plants. *J. Environ. Qual.* 14, 40-46.

Sebacher, D. I., R. C. Harriss, K. B. Bartlett, S. M. Sebacher, and S. S. Grice, 1986. Atmospheric methane sources: Alaskan tundra bogs, and alpine fen and a subarctic boreal marsh. *Tellus* 38B, 1-10.

Seiler, W. and P. J. Crutzen, 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change* 2, 207-247.

Stocks, B. J., 1991. The extent and impact of forest fires in northern circumpolar countries. In J. S Levine (ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, Mass., pp.197-202.

Svensson, B. H., 1980. Carbon dioxide and methane fluxes from the ombrotropic parts of a subarctic mire. Ecol Bull. 30, 235-250.

Wood, C. A. and R. Nelson, 1991. Astronaut observations of global biomass burning. In J. S Levine (ed.), Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. MIT Press, Cambridge, Mass., pp. 29-40.

World Meteorological Organization (WMO), 1991. Report of the WMO Meeting of Experts on the Atmospheric Part of the Joint U.N. Response to the Kuwait Oilfield Fires. World Meteorological Organization, Geneva, Switzerland, 103 pp.

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