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Atmospheric trace gas emissions from tropical Australian savanna fires

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ABSTRACT

Frequent and often annual fires are a major feature of the savannas of northern Australia, but the role of emissions from these fires in atmospheric chemistry remains poorly quantified. The fuel of these fires is normally grass and leaf litter. Fire intensities are relatively low and crown fires are rare. In this paper, the results are presented of measurements of the prompt release of trace gases from savanna fires at Kapalga, NT. The emission ratios of carbon species from the Kapalga fires were similar to those measured in savannas elsewhere in the world. The production of photochemical smog and hence tropospheric ozone is probably one of the main undesirable impacts of these fires on the atmosphere. The effects of possible fire management options on the trace gas emissions were considered by simple modelling of the dynamics of fuel loads and fire intensities. Reducing the fire frequency would increase the likelihood of fire intensities being sufficiently high to reduce the tree cover, with a consequent net release of carbon and nitrogen into the atmosphere. The release of trace gases in the absence of fires needs to be quantified to enable more complete modelling of consequences for the atmosphere of different management regimes.

INTRODUCTION

Biomass burning, especially in the tropics, is now considered to be a globally significant source of atmospheric trace gases (e.g. CO and CH_4) (Crutzen and Andreae 1990), yet at present the global emissions of trace gases from biomass fires are poorly quantified. Until more comprehensive data on trace gas emissions, burning efficiencies, fuel loads and fire frequencies are compiled, the impacts of biomass burning on the atmosphere cannot be assessed accurately. Most fires in the tropics are lit by humans, and this information would help provide a rational basis for modifying existing fire regimes in order to alter the release of trace gases.

In the northern sub-coastal zone of the Northern Territory, fires typically occur in two years out of three (Braithwaite and Estbergs 1985). This frequency of fires is among the highest in the world. Although the fuel loads are relatively low compared with biomass fuels in other vegetation types such as temperate Australian forests (Walker *et al.* 1986), the average amount of fuel consumed *per year* is higher in savannas because of the extremely high fire frequency. Hence the pyrogenic release of carbon and nitrogen gases per year will be higher. In this paper, we report measurements of the prompt release of several important trace gases during fires in the savannas of Kakadu National Park in the Northern Territory. Preliminary data are also presented on the changes in fuel loads and fire intensities with increasing period without fire. The implications of these data for manipulating fire regimes to minimize the emissions of greenhouse gases are discussed.

MATERIALS AND METHODS

Study Site

Kapalga Research Station is 180 km east of Darwin and within Kakadu National Park. The upland ridge between the South Alligator and West Alligator Rivers has been divided into management compartments which represent the catchments of intermittent streams. Each compartment is 15-20 km^2 in area and surrounded by fire breaks. The dominant vegetation of the upland ridge of Kapalga is open forest of *Eucalyptus miniata* and *E. tetrodonta* with the understorey dominated by the annual grass *Sorghum intrans* and perennial grasses such as *Heteropogon triticeus*.

Four experimental fire regimes have been imposed on thirteen compartments on Kapalga. The fire regimes are as follows:

1. 'Early dry season annual'; burnt each year during the early dry season (June). (Compartments E, K, and P.)

2. 'Progressive'; burnt three times during the dry season each year (June, July and September). (Compartments A, B, and H.)

3. 'Late dry season'; burnt each year during the late dry season (September). (Compartments F, G, and L.)

4. 'Natural'; unburnt control; fire is actively excluded from these compartments. (Compartments C, M, Q, and S.)

The first experimental fires were imposed in 1990. Fire had been excluded from the compartments for either two or three years before 1990.

Smoke Sampling

Smoke samples were collected from the ground in June and September 1991 using evacuated 0.6 L glass flasks. The type of combustion that occurred at the point of sampling was classified as flaming or smouldering. Samples of 'clean' air were collected upwind of each fire site for the determination of the background *mixing ratios* of each trace gas. The mixing ratio is defined as the ratio of the mass of a given gas to that of the remaining gas in a mixture. In September 1991 and September 1992, samples of smoke were collected at low altitude (50-700 m above ground) from an aircraft as it traversed fresh smoke plumes. Samples of 'clean' air were also collected a short distance upwind of the fire sites for the determination of background mixing ratios. Further details of the methods for sampling the smoke are presented by Hurst *et al.* (1994).

The *excess mixing ratios* were calculated as the difference between the background mixing ratios for each gas and the respective mixing ratios in the smoke samples. The excess mixing ratios for three carbon species are designated in the text as DCO_2, DCO, and DCH_4. The *emission ratios* for carbon monoxide and methane were defined as the ratios between the excess mixing ratios of these gases and that of carbon dioxide. That is DCO/DCO_2 and DCH_4/DCO_2 respectively.

The concentrations of carbon species were measured in the samples using a Fourier-transform infrared (FTIR) spectrometer and matrix-isolation FTIR spectroscopy (Hurst *et al.* 1994). The nitrogen species NO, NO_x and NH_3 were measured using a chemiluminescence analyser (Hurst *et al.* 1994).

Fuel Loads

Fuel loads were measured each year since 1990 in permanent 20 m *x* 50 m plots situated within the *E. miniata, E. tetrodonta* open forest on each compartment. The fuel load in each plot was estimated annually as the mean of the herbaceous biomass and litter within eight randomly placed 0.25 m^2 quadrats. The measured fuel loads represented sites with a range of periods without fire from 1 to 6 years. Sites where fire has been excluded for more than two years are rare in this region, and these data represent some of the only available measurements of fuel loads under these conditions.

RESULTS

Emission Ratios of Carbon Species and Combustion Efficiencies

No significant differences in the emissions of trace gases were detected between the samples collected during the June fires and those in September. Therefore the data were bulked irrespective of time of sampling. In Table 1 is shown the mean emission ratios for carbon monoxide and methane for ground-based smoke samples collected from flaming and smouldering fires at Kapalga and for aircraft-based samples from fires at Kapalga. These values are compared with measured values from savanna fires in Côte d'Ivoire and Brazil, and from forest fires in the Sydney region.

The mean carbon monoxide and methane emission ratios of ground-based smoke samples were lower for flaming fires than for smouldering fires in both savanna fires at Kapalga and forest fires near Sydney (Table 1). While the emission ratios were similar for flaming fires in both the savanna and the forest, the values for smouldering fires were lower for the savanna than the forest (Table 1). This indicates that the combustion efficiencies were greater for flaming fires than smouldering fires generally, but that smouldering fires in the savanna had a greater combustion efficiency than in the forest.

The carbon monoxide and methane emission ratios for aircraft-based samples from the savanna fires at Kapalga were in good agreement with those measured from savanna fires in Brazil and Côte d'Ivoire. The values for the aircraft-based samples were between those for ground-based samples of smoke from flaming and smouldering fires in both Sydney and Kapalga (Table 1). The values were, however, higher for forest fires than for savanna fires, indicating a greater overall combustion efficiency for savanna fires. It was calculated from these values that between 69 per cent and 74 per cent of the carbon consumed by the savanna fires at Kapalga is released by flaming combustion compared with between 52 per cent and 57 per cent in the forest fire (Table 1).

Partitioning of Carbon and Nitrogen During the Fires.

The partitioning of the fuel carbon and nitrogen during the fires can be estimated by calculating the *emission factors* of each gaseous species and determining the amounts of carbon and nitrogen which remained in the ash after combustion. These were calculated as described by Hurst *et al.* (1984). The partitioning of carbon and nitrogen during the fires is shown as pie charts in Figures 1 and 2 respectively.

TABLE 1

The DCO/DCO2 and DCH4/DCO2 emission ratios of smoke samples from savanna fires at Kapalga, compared with the ratios from forest fires in the Sydney region and savanna fires in Côte d'Ivoire and Brazil. The percentage contribution of flaming combustion to the overall combustion was calculated from the values. Numbers in parentheses indicate standard deviations.

SITE	MEAN EMISSION RATIO			C RELEASE BY FLAMING COMBUSTION (%)
	FLAMING FIRE (GROUND-BASED)	SMOULDERING FIRE (GROUND-BASED)	TOTAL FIRE (AIRCRAFT-BASED)	
DCO/DCO_2				
Kapalga	0.055 (0.023)	0.168 (0.027)	0.090 (0.026)	69
Sydney[a]	0.05	0.175	0.11	52
Brazil & Côte d'Ivoire[b]	-	-	0.053 - 0.113	-
DCH_4/DCO_2				
Kapalga	0.0021 (0.0015)	0.0101 (0.0039)	0.0042 (0.0019)	74
Sydney[a]	0.0022	0.013	0.0068	57
Côte d'Ivoire[c]	-	-	0.0038 (0.0011)	

[a] D. Griffith, unpublished data.

[b] Greenberg *et al.* 1984; Bonsang *et al.* 1991; Lobert *et al.* 1991; Ward *et al.* 1992.

[c] Delmas *et al.* 1991.

The combined emissions of CO_2, CO, CH_4, total non-methane hydrocarbons (NMHC) and particulate carbon (PC) approximates all carbon-containing emissions. Carbon emissions were dominated by CO_2 which represented 86.8±2.8 per cent (± standard deviation) of the fuel carbon, while CO accounted for 7.8±2.3 per cent (Fig. 1). Emissions of total NMHC and CH_4 comprised less than 1 per cent each of the fuel carbon.

The nitrogen-containing emissions could only be partitioned to NO_x, NH_3, N_2O, HCN, CH_3CN and ash. The measured nitrogen emissions were dominated by NO_x (21±8 per cent of fuel N) and NH_3 (23±13 per cent) with N_2O, HCN, and CH_3CN each representing less than 1 per cent of the fuel nitrogen. The emission factors for NO_x, NH_3, N_2O, HCN, and CH_3CN together accounted for only 46±15 per cent of the fuel nitrogen. The nitrogen contained in the ash represented 11±5 per cent of the fuel nitrogen, so in total, our measurements accounted for only 56±16 per cent of the fuel nitrogen. This shortfall in detected nitrogen-containing emissions from biomass burning is now well documented, and recent experimental evidence indicates that 33±13 per cent of fuel nitrogen is emitted as N_2 during flaming combustion (Kuhlbusch *et al.* 1991). Any remainder of the undetected fuel nitrogen may have been emitted as higher molecular weight compounds.

Fire Behaviour and Fuel Consumption Under Different Fire Management Options

The mean biomass of fuel and fire intensity of plots on Kapalga with varying period without fire is presented in Table 2. Fuel loads were least under annual fires, but there was no evidence that fuel continued to accumulate after about two to three years without a fire. The available evidence indicates that fire intensities tend to be greater on sites that have not been burnt for two or more years than on annually burnt sites. Fire intensities also tended to be greater for late dry season fires than early (see Williams, this volume).

DISCUSSION

The release of trace gases from fires in the savannas at Kapalga appears to be similar to that from savannas in other parts of the world (Table 1). A characteristic feature of savannas is the prevalence of grassy fuels, in contrast to greater importance of woody fuels in forest communities. The dominance of flaming combustion and the greater overall combustion efficiency of the savanna fires compared with forest fires in southern Australia (Table 1) is consistent with these differences in fuel types.

TABLE 2

The measured fuel load and fire intensity of experimental compartments at Kapalga with varying periods without fire in the years from 1990-1993.

PERIOD WITHOUT FIRE (Y)	COMPARTMENTS	YEAR	FUEL LOAD (T HA^{-1}) *	MEAN FIRE INTENSITY ** ($kW\ m^{-1} \times 10^3$) EARLY	LATE
1	A, E, F, G, H, & P	1991, 1992, & 1993	5.1 (1.4)[a]	1.7 (n = 10)	5.2 (n = 4)
2	F & P	1990	7.8 (1.7)[b]	10 (n = 1)	-
3	A, C, E, G, H, & M	1990	10.3 (0.9)[c]	10 (n = 1)	15 (n = 1)
4	C & M	1991	8.1 (1.0)[bc]	-	-
5	C & M	1992	8.5 (0.2)[bc]	-	-
6	C & M	1993	6.8 (1.7)[ab]	-	-

* different letters indicate significant differences ($p < 0.05$).

** A.M. Gill, R.J. Williams and P. Moore: unpublished data; data were not available for all fires.

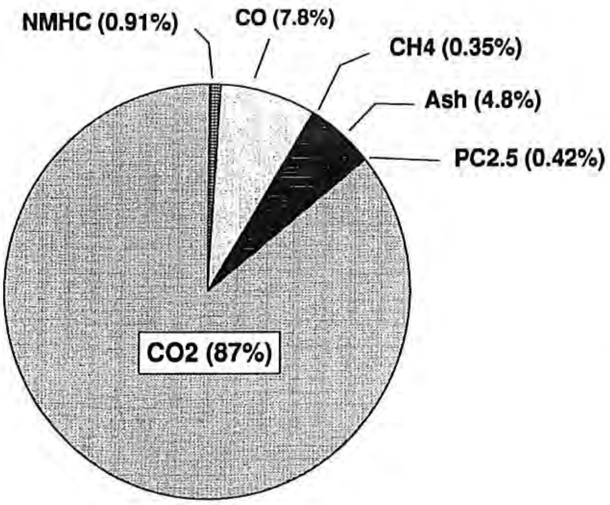

Figure 1. Partitioning of fuel carbon during savanna fires at Kapalga. PC 2.5 is emitted particulate carbon (<2.5 mm diameter, see Hurst et al. *1994).*

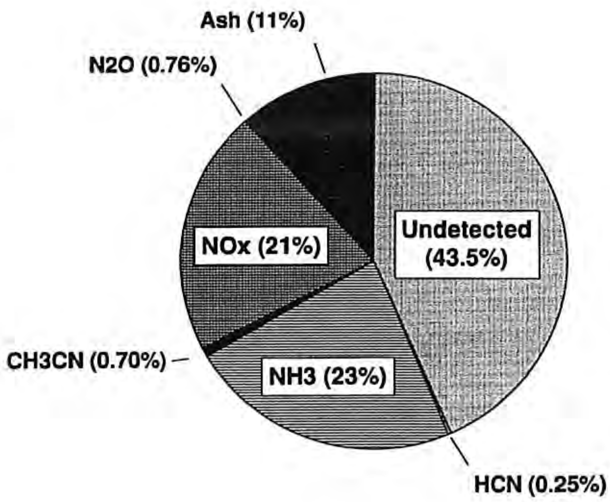

Figure 2. Partitioning of fuel nitrogen during savanna fires at Kapalga.

Carbon dioxide, which was the main carbon species released during the fires at Kapalga (Fig. 1), is a major greenhouse gas in the atmosphere. However, if the structure and productivity of the savanna vegetation is not changing over time, then the growth of vegetation in the weeks and months after each fire should take up similar amounts of carbon to that released. Thus, the net release of carbon to the atmosphere should be close to zero in this region because there is little evidence of substantial changes in vegetation structure of savannas in the region in response to fire (Bowman *et al.* 1988; Lonsdale and Braithwaite 1991). Nevertheless, there are concerns that present fire regimes are limiting the recruitment of woody species which may lead to reduced tree cover (Duff and Braithwaite 1989). If this is occurring, then the result would be a positive net release of carbon and possibly a reduced capacity to absorb and store carbon.

The other greenhouse gases released during the fires, methane and nitrous oxide, were both released in small amounts (Figs 1 and 2). It has been estimated that the methane released from biomass burning in Australian savannas represents about 10 per cent of all methane sources in Australia (Hurst *et al.* 1994). In contrast, the release of nitrous oxide by savanna fires represents less than 3 per cent of other natural and anthropogenic sources.

The gases CO, CH_4, NMHC, and NO_x which were released in significant quantities by the fires at Kapalga (Figs 1 and 2) are precursors to the formation of photochemical smog. The production of photochemical smog from these gases is recognized as an important consequence of biomass burning in Africa and South America (Cros *et al.* 1991). Photochemical smog in turn, leads to the formation of tropospheric ozone, which is a very effective, albeit short-lived, greenhouse gas. Although tropospheric ozone was not measured as part of this study, its formation is likely to be one of the main undesirable consequences of the gaseous emissions from the fires in Australia's northern savannas.

If one wishes to manage the savannas to minimize the production of greenhouse gases, it cannot be achieved by simply reducing fire frequency from almost annual to one in two or one in three years. Although the *per year* consumption of grassy fuel by fire would decrease if fire frequency were reduced, the intensity of fires would tend to increase because the fuel loads are greater (Table 2). As well, there is no evidence that soil organic matter levels increase when fires are excluded from these savannas (Cook, unpublished data). With greater fire intensities tree death is likely to increase (see Williams, this volume). As a consequence, the carbon and nitrogen which had been stored in the tree stems would be released to the atmosphere due to decay and combustion over several years. Thus a positive net release of carbon and nitrogen could result from reducing fire frequency if this is accompanied by increased death of trees. As well, proportionately more methane would be released because the stems of the trees would burn by smouldering fires rather than by flaming fires (see Table 1).

The fate of the 'fuel' in the absence of fire must also be accounted for in modelling the effects of different fire regime on trace gas emissions. Fuel loads at Kapalga did not continue to increase after three years without fire (Table 2). This indicates that biological oxidation of organic matter is of major importance in these savannas. The emissions of trace gases during the biological oxidation of the 'fuel' are more difficult to measure than pyrogenic emissions because of their greater spatial and temporal variability. Some evidence suggests that biological oxidation may release more greenhouse gases than pyrogenic oxidation. Termites, for example, release about 1.2 per cent of the carbon they consume as methane (Khalil *et al.* 1990; Holt 1991) compared with only 0.35 per cent for fires at Kapalga (Fig. 2). As well, termites may release a greater proportion of nitrous oxide per unit of biomass consumed than fires. Further work is required to quantify these biogenic emissions.

CONCLUSIONS

The release of trace gases from fires at Kapalga was similar to that from savannas elsewhere in the world. The net release of carbon and nitrogen is likely to be close to zero under present fire regimes because the structure and productivity of these savannas does not appear to be changing. The main undesirable effect of these fires on the atmosphere is likely to be the production of photochemical smog and hence tropospheric ozone. It may be possible to change the present fire regimes to minimize the production of precursors to photochemical smog. If fire frequencies were reduced substantially, the biological oxidation of unburnt biomass may release equivalent or even greater quantities of trace gases than those from fires, but would also predispose the savannas to more intense fires resulting in greater tree death. Maintaining a regime of frequent but low intensity and patchy fires is probably the best practical way to minimize the release of undesirable trace gases.

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