Assessing Fire Emissions from Tropical Savanna and Forests of Central Brazil

Abstract
Wildfires in tropical forest and savanna are a strong source of trace gas and particulate emissions to the atmosphere, but estimates of the continental-scale impacts are limited by large uncertainties in the rates of fire occurrence and biomass combustion. Satellite-based remote sensing offers promise for characterizing fire physical properties and impacts on the environment, but currently available sensors saturate over high-radiance targets and provide only indications of regions and times at which fires are extensive and their areal rate of growth as recorded in ash layers. Here we describe an approach combining satellite- and aircraft-based remote sensing with in situ *measurements of smoke to estimate emissions from central Brazil. These estimates will improve global accounting of radiation-absorbing gases and particulates that may be contributing to climate change and will provide strategic data for fire management.*

Introduction

Global Atmospheric Effects of Wildland Fires
Flying northward from Brasília to Belém during the dry season, one sees compelling evidence of fire's force on the Brazilian landscape. There are hundreds of small agricultural fires in the tropical savanna or Cerrado. Fires in slashed moist forest near Marabá burn furiously for hours, with towering smoke columns and capping cumulus reaching to near 8,000 metres. A smoke pall extending over thousands of square kilometres nearly obscures the ground along the Transamazonia Highway. Such fires are pervasive in tropical savanna and forests on the frontier of human settlement, not just in Brazil, but throughout the tropics. The associated combustion emissions are now thought to constitute an important anthropogenic source of atmospheric aerosols and trace gases, such as methane, carbon monoxide, carbon dioxide, and some nitrogen oxides, that affect the Earth's radiation balance and global climate (Crutzen and Andreae, 1990; Radke *et al.*, 1991; Seiler and Conrad, 1987). The direction and magnitude of a possible climate impact are not well established, however. Current estimates of global fire extent, and thereby emissions, are inexact and come from uneven reporting of fire occurrence and from calculations based on growth of human population and land use (Seiler and Crutzen, 1980).

Fires of human origin could be contributing in two ways to rising atmospheric concentrations of radiation-absorbing trace gases: (1) if over the long-term they reduce the amount of carbon accumulated in standing biomass or soils, or (2) if they emit a higher proportion of methane, carbon monoxide, or nitrous oxide than would alternative biological pathways of organic matter decomposition. Such changes are tantamount to an increase in emissions flux above that occurring prior to modern human occupation and the attendant rise in the rate of fire ignitions.

Emissions of particles above those found with a natural fire regime could well dominate the radiative effects. A high proportion of smoke particles are active as cloud condensation nuclei (Hobbs and Radke, 1969; Radke, 1989; Radke *et al.*, 1991; Rogers *et al.*, 1991), and their entrainment in clouds can produce more numerous droplets of smaller diameter, thereby increasing cloud albedo and possibly liquid water content and cloudiness. Together with their direct radiative effects, aerosols from biomass combustion could be responsible for a global cooling as great as 2 watts m^{-2}, comparable in magnitude and opposite in sign to the radiative effects expected from increases of greenhouse gases during the last century (Penner *et al.*, 1991; 1992).

The net effect of human-caused fires will be difficult to assess, requiring knowledge of the change in stored carbon where fires are not natural or past emission rates where they are. Yet reliable estimates of contemporary emissions from burning may be achievable, and could cause us to reject the hypothesis that fires are an important factor in climate change if emissions prove to be small in relation to other anthropogenic sources.

A Synoptic Approach
As with many problems in global change, what we need in order to determine the magnitude of combustion emissions are synoptic measurements of the phenomenon on a continental if not global scale. Remote sensing of fire properties could at least partially provide this synoptic view. In this paper we consider the utility of currently available remote sensing systems for this purpose and describe a means for conducting a continental-scale assessment of fire emissions to the atmosphere, emphasizing emissions from central Brazil. Such an assessment is an integral part of cooperative efforts by the governments of Brazil and the United States to develop approaches for reducing the extent and environmental impact of widespread burning in tropical forests and savanna.

Contemporary fire emissions from a source region can be estimated as the time-integrated product of (1) area burned per unit time, (2) biomass consumption per unit area, and (3)

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emissions per mass consumed (referred to as an emission factor). Remote sensing can provide a wide-area estimate of areal fire growth from a change detection of post-fire ash. It can also be applied to a regionally stratified sample of active fires to estimate their radiant energy flux, which we expect to be a predictor of the biomass consumption rate. Radiant energy flux from entire fires can also be used to stratify airborne measurements of emission factors. Satellite-based systems that are now operational are adequate for mapping ash and detecting regional fire activity, but they do not allow an unbiased estimate of radiant energy flux. However, recent developments in high-resolution aircraft-based spectrometers may provide a means to bridge this gap in measurements.

Remote Sensing Wildland Fires

Synoptic Fire Detection with the AVHRR

Data from the Advanced Very High Resolution Radiometers (AVHRR), operated by the U.S. National Oceanic and Atmospheric Administration, provide indications of regions and times at which fires are extensive at a continental scale (Plate 1). Fire radiant emissions may be detected with the instrument's 3.55- to 3.93-μm and 10.3- to 12.5-μm channels with a sampling frequency of four observations per day, although small fires can be unambiguously discriminated only from the 3.55- to 3.93-μm channel used at night. At wavelengths of 10.3 to 12.5 μm, emitted energy of small fires may be indistinguishable from that of the background within the nominally 1-km² picture element of the sensor (Matson *et al.*, 1984), and during the day specular reflection from bare ground can produce bright targets at 3.55 to 3.93 μm. In Brazil, specular reflection is apparently a problem in the region of the Caatinga, a thorn scrub vegetation in the northeast of the country (A. Setzer, personal communication). It is probably less common in tropical savanna with a relatively continuous cover of grasses.

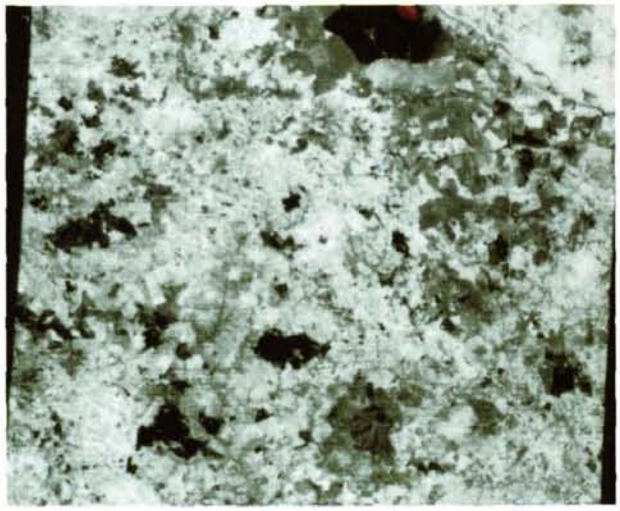

Plate 1. Fire occurrence in central Brazil as recorded by the 3.55- to 3.93-μm channel of the NOAA Advanced Very High Resolution Radiometer for 1 to 15 July 1988. Each of the bright pixels represents approximately a 1-km² area in which at least one fire was inferred to be burning. Background in the image depicts regional variation in the normalized difference vegetation index. Rio de Janeiro is on the southeastern coast at the lower right; the Paraguay River is visible on the left (image courtesy of Dr. Alberto Setzer, INPE).

A census of fire occurrence from AVHRR data requires interpretation because of the difficulties of small fire detection and because persistent fires may be detected on several occasions, large fires extend across many pixels, and bright pixels may represent more than one fire. Nonetheless, the 3.55- to 3.93-μm channel of the AVHRR is now routinely used by the Instituto Nacional de Pesquisas Espaciais (INPE), the Brazilian Space Research Institute, to detect fires across Brazil and especially in key conservation areas. The results are mapped and reported weekly during the fire season in the *Folha de São Paulo* newspaper. During 1991 over 500,000 fires were inferred (A. Setzer, personal communication). Such reports have documented the geographical breadth of the fire problem in Brazil and have stirred deep environmental concern. Yet these data provide little insight to fire's ultimate impact on the environment.

Mapping Fire Areas

The final area over which a fire spreads can readily be obtained by mapping post-fire ash. In relation to unburned vegetation, ash is of very low reflectance in the near infrared, and bright at intermediate and long infrared wavelengths (Riggan *et al.*, in press). Yet problems in determining fire size will arise when the perimeter of the fire is large in relation to its area, as with mosaics of burned and unburned vegetation, or when the burned area is small in relation to the pixel size and sub-pixel resolution must be obtained. In this case a low variance in radiance across background pixels and a strong contrast between the background and ash is required.

Data of high spatial resolution, such as that provided by the Landsat MultiSpectral Scanner (MSS) or Thematic Mapper (TM), give the best discrimination of ash and yield the most accurate estimates of fire area. Areal *progression* of fires across the landscape, as we require, could be obtained by summing the area of ash that first appears over the time interval between successive images. The sampling interval would have to be sufficiently brief — say, 4 to 6 weeks in tropical savanna — to assure that recently burned areas are not obscured by vegetation growth during the interval. In the absence of such growth and substantial rainfall, ash will persist and can be readily detected for a period of months. Landsat provides data of coarse but generally adequate time resolution — 16 days at best, perhaps months at worst, because of cloud cover.

TM channels 4, 6, and 7 would provide the best discrimination of post-fire ash, but near-infrared data from MSS is adequate (Plate 2) and much more cost-effective. Near-infrared data can be used to map ash even when dispersed smoke is present, but dense smoke plumes will obscure a scene. Because accurate radiometric calibration is not necessary for this purpose, our initial approach has been to use data obtained by digitizing MSS photo transparencies.

The nominally 1-km² data from the AVHRR could be used to map ash-covered landscapes over wide areas with high temporal resolution, but some sub-pixel estimates would be necessary in order to avoid potentially large errors in estimating areas of fires smaller than several hundred hectares. Development of a difference image from successive scenes could also be problematic for fires of sub-pixel resolution because it is difficult to know whether a small fire has been previously detected. The difficulty is compounded by registration errors between successive orbits, and can only be ex-

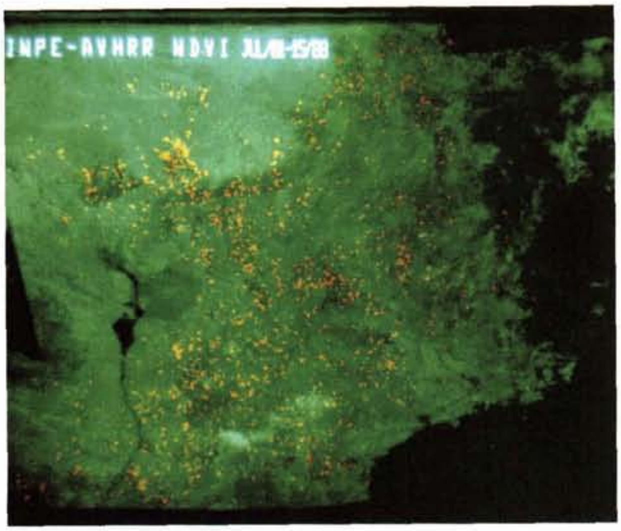

Plate 2. Fire area mapping in tropical savanna and agricultural lands south of Emas National Park, Goías, Brazil with data from MSS channel 4. Recent fires, shown here by a black overlay, are readily detectable by very low reflectance at near-infrared wavelengths. The large burned area at the top is centered within the National Park.

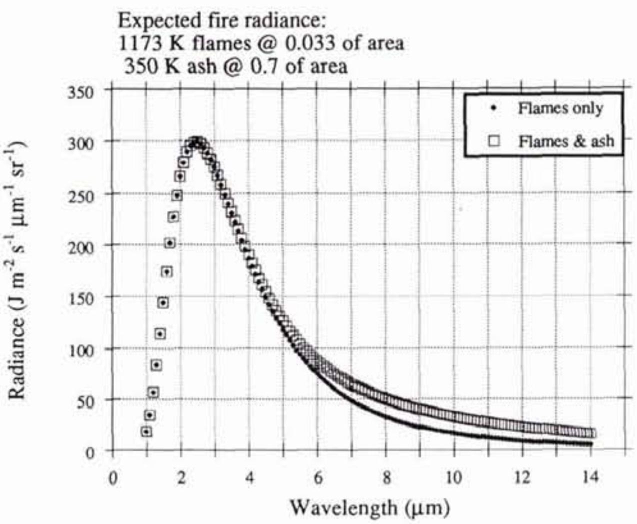

Figure 1. Model radiance of emitted energy, estimated by the Planck function, of a portion of a savanna fire as might be viewed with a sensor of approximately 30-m resolution. Here we have assumed that 0.033 of the local area is occupied by flames at a temperature of 1173 K, 0.6 of the area is occupied by ash at 350 K, and the remainder is covered by vegetation at 300 K. Ash contributes 12 percent of the total emitted radiance and is important only at wavelengths longer than 5 µm.

acerbated by recent Brazilian regulations stipulating that agricultural fires must remain under 50 ha (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, personal communication).

Fire Temperatures and Radiant Energy Flux

Active wildland fires present a complex target for remote sensing that may be broadly characterized as a gradient of temperatures and radiances from the spreading fire front through residual flaming, smoldering combustion, and cooling ash. Peak temperatures of flames[1] in burning chaparral or logging slash are typically in the range of 1100 to 1200 K at 1 m aboveground, with occasional values near 1300 K (F. Weirich, unpublished report on file, USDA Forest Service, Riverside, California). Temperatures at the surface of mineral soil beneath flaming combustion approach those of the flames (1100 to 1200 K). Ash surface temperatures after passage of intense fires, as occur in chaparral, can remain above 700 K for one to two minutes and as high as 345 K under solar heating (Riggan *et al.*, in press). Peak flame temperatures of 1000 to 1100 K and much lower energy yields have been observed during fires in Brazilian savanna (A. Miranda, personal communication).

Flames and ash at peak temperatures are very bright at intermediate infrared wavelengths; blackbody radiation at 1173 K, for example, is maximal at a wavelength of 2.5 µm (Figure 1). The radiance of a blackbody at 11 µm and 1173 K is 38 times that emitted at a more common terrestrial temperature of 300 K. Ash at the intermediate temperature of, say, 700 K contributes to the radiance of the fire environment primarily at longer wavelengths (Figure 1).

Although fire temperatures apparently vary little across a range of wildland fire conditions, the radiance or energy release rate per metre of fire line in a spreading fire can change by orders of magnitude across different fires or even within a fire complex. In North America, flame lengths and depth of the flaming zone can vary from less than 1 m in grass or burning ground fuels to 30 metres or more in intense chaparral fires and perhaps twice this latter value in crown fires in coniferous forest.

Attenuation by Smoke

Dispersing smoke from wildland fires apparently causes little attenuation of infrared radiation at wavelengths longer than 1.5 µm, except in water or CO_2 absorption bands, as can be demonstrated as follows for a horizontal layer emanating from a plume in southern California. The fraction of incident radiation, I/I_o, that is transmitted through the layer can be described as an exponential function, $I/I_o = e^{-\tau}$, of the layer's optical depth, τ. τ is determined by scattering and absorption in the smoke aerosol and varies with wavelength, λ. τ can be computed as the product of smoke density (g/m³), the layer thickness (m), and the mass-specific optical extinction coefficient, b_e (m²/g). At $\lambda = 0.54$ µm we estimate $b_e = 2.3$ m²/g from the absorption coefficient, b_a, and the ratio of scattering to extinction coefficients given by Radke *et al.* (1988)[2]. Thus, given a smoke density of 1.2×10^{-3} g/m² (measured at the Lodi II Fire; L.F. Radke, personal communication), we estimate $\tau = 1.4$ at $\lambda = 0.54$. Pueschel *et al.* (1988) estimated optical depths for such smoke with a sun photometer and described τ as a power function, $\tau \propto \lambda^a$, with the Angstrom

[1]As measured with unshielded, 30-gauge, type-K thermocouples at a sampling rate of 1 s⁻¹. With a narrow flaming zone and fast rate of spread, this method may underestimate the true temperature.

[2]where $b_a = b_e - b_s = 0.46$ m²/g, $b_s/b_e = 0.8$, and b_s (m²/g) is a scattering coefficient.

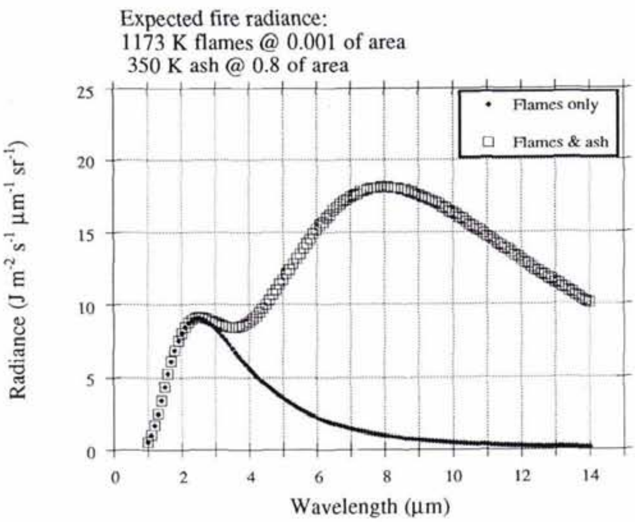

Figure 2. Model radiance of emitted energy of a savanna fire as might be viewed by the AVHRR, in which 0.001 of the area is in flames, 0.6 is in ash, and the remainder is vegetation. Here the composite distribution of radiances departs markedly from a simple Planck function. The radiance of ash may also have a strong component of reflected solar radiation at short infrared wavelengths that further complicates the extraction of information regarding the flaming zone.

coefficient, a, estimated to be -2.4. Calculating a proportionality constant from our computed value of τ at 0.54 µm, we estimate that a 500-m smoke layer will produce a 6 percent attenuation of upwelling radiation at the 1.65-µm wavelength and less than 1 percent attenuation at wavelengths longer than 4 µm.

Attenuation of upwelling radiation by a vertical plume of 3000 m with equivalent smoke properties would be approximately 45 percent at 1.65 µm and 7 percent at 4 µm. Water clouds completely obscure upwelling radiation, and such organized smoke plumes in the tropics are generally capped by cumulus. These problems can be circumvented by aircraft sampling from alongside such an obstruction, but fire measurements from satellite platforms with a nadir view will be severely compromised where a strong plume rises vertically.

Estimating Fire Radiance

The fractional area, A, and temperature, T, of a high-temperature target within a pixel can be estimated from the emitted energy measured at two wavelengths, λ_1 and λ_2, if the target behaves as a blackbody and the radiance of the low-temperature background can be estimated from nearby pixels (Matson and Dozier, 1981). Of course, the target's radiance must be great enough to be discriminated but low enough not to saturate the remote sensing system at those wavelengths. If the spatial resolution of the sensor is high in relation to the dimensions of the target, then the background radiance can be ignored and Planck functions for the target radiances, B_{λ_2} and B_{λ_1}, may be solved simultaneously, yielding the relations

$$B_{\lambda_2}/B_{\lambda_1} = \lambda_1^5(e^{hc/k\lambda_1 T} - 1)/\lambda_2^5(e^{hc/k\lambda_2 T} - 1) \quad (1)$$

and

$$A = B_{\lambda_i}\lambda_i^5(e^{hc/k\lambda_i T} - 1)/(2 \times 10^{-6} hc^2) \quad (2)$$

where h is the Planck constant, 6.63×10^{-34} (J s); c is the speed of light, 3.00×10^8 (m/s); k is the Boltzmann constant, 1.38×10^{-23} (J/K); T is specified in Kelvins; λ is in metres; and B_λ is specified in J m^{-2} s^{-1} sr^{-1} µm^{-1}. T can be iteratively computed from Equation 1 and A can be computed from either wavelength. The wavelength-integrated radiance, B (J m^{-2} s^{-1} sr^{-1}), is computed by evaluating the function $B = (A\sigma/\pi)T^4$, where σ is the Stefan Boltzmann constant, 5.67×10^{-8} J m^{-2} s^{-1} K^{-4} (Liou, 1980).

Total radiance per metre of the flaming front can then be integrated across time for fires spreading at a steady rate in uniform fuels. With this steady-state assumption, pixels immediately behind the fire front provide a measure of the course of fire activity and soil radiance at a given time after passage of the front. The elapsed time can be estimated from the rate of spread as viewed between successive images. The time interval between these images must be relatively small so as to represent relatively constant burning conditions yet long enough to permit a reasonable discrimination of the spread rate given the resolution of the sensor.

Upwelling radiation common for large wildland fires, including some spreading fires in tropical savanna, will saturate TM channels 6 and 7 and the 3.55- to 3.93-µm channel of the AVHRR (A. Setzer, personal communication; Brustet *et al.*, 1991). Thus, a statistical distribution of fire radiances derived from either sensor would be biased, even though a substantial portion of fires in the tropics may be sampled (A. Setzer, personal communication). This bias would compromise a regional estimate of combustion emissions derived from the data, especially because larger fires are likely to dominate those emissions.

Even when the pixel area is much larger than the scale of the flaming zone and the sensor remains unsaturated, as when a small savanna fire is viewed by the AVHRR, the pixel necessarily encompasses the entire thermal gradient of flame and ash. The assumption of a binary system of fire and background is violated, and the estimated areas and temperatures are not readily interpretable in terms of fire properties. Furthermore, if the flaming zone is not the dominant source of emitted energy, the radiator will be at best a mixture of two or more blackbody sources and the Planck function evaluated at the composite temperature could be a poor estimator of the wavelength-integrated radiance (Figure 2).

We have recently developed an aircraft-based fire-imaging spectrometer capable of quantitative measurements of the very high radiances associated with large wildland fires. This spectrometer incorporates the chassis and optical system of a Texas Instruments[3] RS-25 thermal line scanner. It is a four-channel, 14-bit digital system with detectors of silicon, indium-gallium arsenide, indium antimonide, and mercury-cadmium telluride, the latter two in a sandwich-detector design. We have chosen an initial configuration with channels at wavelengths of 0.58 to 0.7 µm, 1.55 to 1.75 µm, 3.95 to 4.05 µm, and 10 to 12 µm. Spatial resolution is approximately 2.5 m per 1000 m of altitude above ground.

The three infrared channels of the spectrometer have been calibrated in the laboratory to temperatures as high as 900 K. The target consists of a 23- by 48- by 0.6-cm brass plate to which was applied a 3M solar absorber coating with nominal emissivity of 0.95. The target is heated from below by an array of quartz heaters.

[3]Trade names, commercial products, and enterprises are mentioned solely for information. No endorsement by the U.S. Government is implied.

We deployed the fire-imaging spectrometer in central Brazil in September 1992 aboard a King Air B200t aircraft operated by the National Center for Atmospheric Research and were successful in producing the first multi-channel, unsaturated data over high-intensity fires. We have done a preliminary analysis of two fires: one in the campo limpo (clean field) form of savanna vegetation at the Reserva Ecológica of the Instituto Brasileiro de Geografia e Estatística (the Brazilian Institute of Geography and Statistics) and one in felled tropical forest near Marabá.

The savanna fire was ignited along the perimeter of a 200-ha field under partial cloud cover (Plate 3). It spread with two primary fire lines burning in similar vegetation: one nearly parallel to the ambient wind and one with portions running with the wind. Flame temperatures were similar between the lines, but the energy release rate was several fold greater from that running with the wind. Residual combustion was also apparent along the margin of the nearby gallery forest. Estimated fire temperatures were near expected values; 90 percent fell within the range of 933 to 1336 K. The soil surface apparently radiated little energy after passage of the flaming front because pixels above ambient temperature at the trailing edge of the flaming zone exhibited temperatures similar to those of the leading edge where flames surely predominated. Radiances at 1.65 μm in cooled ash and unburned ground were 1 to 2 percent of those observed in the flaming zone.

The fire in felled tropical forest was ignited along the margin of the felled area and burned toward its center. It involved a wide reach of residual combustion behind the interior flaming zone (Plate 4). Flaming activity was much less homogeneous than in the savanna fire. Fire temperatures were similar to those of the savanna fire, with 90 percent of the values within the range from 846 to 1117 K.

It remains to apply individual-fire measurements such as these to a representative sample of the much larger population of fires across central Brazil, stratifying the sample by latitude and major ecosystem type. The approach could be improved by using the regional fire density estimates from the AVHRR to direct effort preferentially, but not entirely, to areas of regionally high fire density.

Atmospheric Sampling

The third set of measurements that we require of tropical fires — the emission factors — have previously been limited to a few aircraft transects through dispersed haze layers associated with burning (e.g., Andreae *et al.*, 1988; Crutzen *et al.*, 1985; Delany *et al.*, 1985), and a small number of ground-level measurements and individual plume measurements from aircraft (Ward *et al.*, 1991a; 1991b). It is not clear whether estimates of emission factors from North America (as reported by Hegg *et al.* (1990), Radke *et al.* (1991), and others), a large number of which are from fires in logging slash, are relevant to burning in Brazil.

Emission factors in North America exhibit considerable variation across major fires; those for carbon monoxide, for example, range from 34 to 175 g kg^{-1} of fuel consumed (Hegg *et al.*, 1990). Recent studies show that there is some consistency among the emission factors of reduced compounds such as carbon monoxide, molecular hydrogen, and methane and of particulates (Radke *et al.*, 1991), but the conditions that produce high or low concentrations of reduced gases are not necessarily predictable other than in a broad sense across fuel type and moisture content. Emission factors for reduced gases and particulates are probably greatest where combustion entails some degree of oxygen depletion: during smoldering combustion, burning of large-diameter or wet fuels, or during extensive and intense flaming combustion (Hegg *et al.*, 1990; Cofer *et al.*, 1989).

High-resolution remote sensing of fire radiant emissions and fire geometry may allow discrimination of some of these effects. The magnitude of smoldering combustion in large-diameter fuels, for instance, would be indicated by a high spatial heterogeneity and residence time after passage of a fire front. Intense flaming combustion, such as might be expected with substantial wind, would be indicated by high radiances and a broad flaming zone. Burning in organic soils within savanna landscapes would typically be spatially discontinuous, of low energy release rate, and along margins of gallery forests. Each of these properties should be readily discernible by remote sensing.

Our aircraft-based remote sensing of fire radiance also provides a way to stratify measurements of the emission factors. The approach is to spend the greatest amount of effort in measuring those fires responsible for the greatest emissions. This would include those which progress across the greatest area of land, produce high concentrations of emissions per unit biomass, or consume the greatest amount of biomass.

Sampling Protocol

In summary, we see satellite- and aircraft-based remote sensing as integral parts of a protocol to assess gross emissions from tropical forests and savannas. A first step is to estimate the areal growth of fires over a period of weeks in central Brazil by change detection of ash-covered landscapes. This synoptic view can best be achieved by mapping with near-infrared photo products from the MSS. Radiant emissions from individual fires can be measured by the aircraft-based fire imaging spectrometer, deployed to sample a range of fire conditions across latitude and ecosystem type. Within a given aircraft transect, sampling regions should be selected based on a stratification of local fire density as indicated by fire detection with the AVHRR. Radiant emissions may then be used to predict biomass combustion rates based on coincident measurements of these variables for a smaller sample of intensively studied fires in major fuel types. Finally, the aircraft remote sensing data can be used as a stratification tool in sampling of individual smoke plumes to estimate emissions per unit of biomass consumption.

If a continental-scale assessment shows that the gross rate of fire emissions is substantial, the next and more difficult task will be to determine how contemporary changes in fire frequency have altered emissions above the more natural, baseline rate. This is a complicated proposition in savanna where fire is a natural disturbance. There the structure and biomass of the vegetation, and thereby the rates of biomass combustion and combustion emissions, may be dramatically altered by changes in fire frequency, occasionally decade-long periods without fire, or long-term nutrient depletion from multiple fires. Remote sensing could play an important role in evaluating both the modern ecosystem change and subsequent changes in fire behavior.

Conclusion

During a research flight this past September we observed a large fire in the Cerrado that serves as a metaphor for fires in central Brazil. Encompassing several thousand hectares, it ran unchecked through grasslands with clearly visible fire lines. Yet these flames produced little smoke, and the source of the massive smoke column emanating from the fire's interior was hidden. The entire fire complex was shrouded from above by stratocumulus, as it pumped tons of smoke parti-

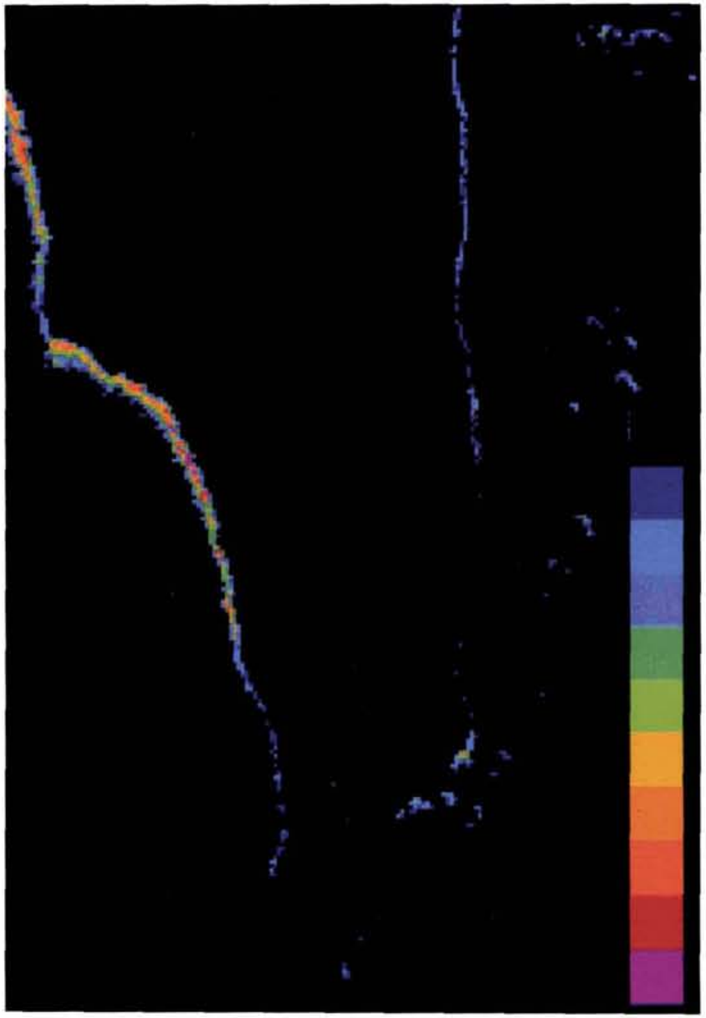

Plate 3. An active prescribed fire in the campo limpo (clean grassland) phase of the Cerrado at the Reserva Ecológica of the Instituto Brasileiro de Geographia e Estatística, Distrito Federal, Brazil, as measured by the Fire Imaging Spectrometer. This density-sliced image depicts the wavelength-integrated fire radiance computed as $(A\sigma/\pi)T^4$ (see text). The color bar depicts increasing radiance from dark blue to magenta in increments of 625 ($J\ m^{-2}\ s^{-1}\ sr^{-1}$). The fire was ignited along a gallery forest at the far right and a roadway to the left of the combustion. Apparent fire-line widths are in scale and show variations in burning conditions. More intense portions of the fire line on the left are propagating with the wind; the line on the right (in blue) is nearly stationary and parallel to the ambient wind field. Detached areas of fire at the far right are largely residual combustion in woody material or ground fuels along the margin of the gallery forest.

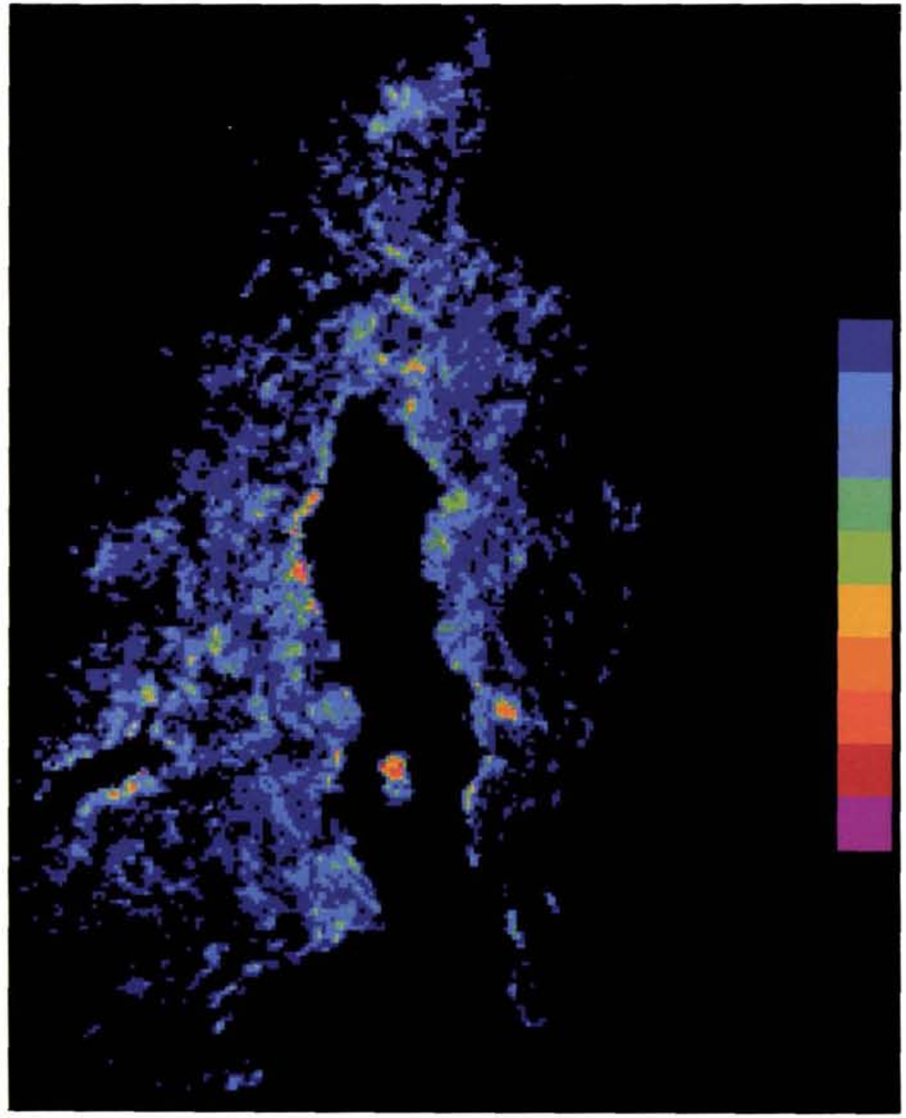

Plate 4. Radiance of fire in slashed tropical forest near Marabá, Pará, Brazil, depicted as a density-sliced image with increments of 1325 ($J\ m^{-2}\ s^{-1}\ sr^{-1}$). A discontinuous fire line is located along the interior of the burned area where residual combustion is widespread. The fire was ignited along the margins of the burned area.

cles into the atmosphere. As with fires in central Brazil as a whole, we could see the flames were a powerful force in the environment, but neither their true extent nor impacts were readily apparent. Management of the fire situation in the tropics will require a definition and understanding of the global impacts. We think remote sensing will be a key to that understanding.

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