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Amazonia Biomass Burnings in 1987 and an Estimate of Their Tropospheric Emissions

Biomass burning in Brazil's Amazon Basin was detected during the dry season of 1987 using 46 images of the AVHRR sensor on board the NOAA-9 satellite. A conservative estimate indicated 350 000 independent fires, corresponding possibly to about twenty million hectares of different types of vegetation burned, of which eight million were associated with recent deforestation. Giant smoke and haze clouds produced by the fires extended over millions of km² and were regularly detected on the continent and spread over the southern Atlantic Ocean. Estimates of emissions from the fires, in millions of tons, were 1700 for CO_2, 94 for CO, 6 for particulates, 9 for ozone (secondary reactions), 10 for CH_4, 1 for NO_x, and 0.1 for CH_3Cl. These emissions caused severe atmospheric pollution effects on a synoptic scale with possible global implications, and should be of high concern in the future following current tropical deforestation and associated biomass burning.

INTRODUCTION

A common practice associated with forest clearings and land management in the Amazon is the burning of the existing vegetation cover. Although there are a large number of biomass burnings every year and adverse effects to the environment are known to result, no efforts have been made to measure the magnitude of these burnings. Despite the fact that any burning must be officially notified and approved, this procedure is seldom followed and therefore there are no statistics for the number of burnings or the area affected. Considering that the burnings occur in a region of many millions of square kilometers, and federal and state forest services are not suited to survey the forest, orbital remote sensing is currently the only viable technique to monitor the Amazon forest on a regular basis. For a summary of recent developments in this field see Malingreau and Tucker(1).

Of the satellites that can be used to monitor large fires, the meteorological NOAA series 850 km high polar orbiters have important features: daily coverage with four daytime and four nighttime passes for any area; multispectral coverage with the same 1.1 km resolution in visible, near, and thermal infrared bands; and a relatively good capability of near real time receiving and processing of images covering areas of continental dimensions.

Landsat/TM and SPOT (30 and 10 m resolution, respectively) can also be used and provide much finer details of the fires and burning areas, but such systems are of limited use for regional monitoring due to the high data volumes associated with the high spatial resolution and the low temporal repeat frequency of many days. The use of the NOAA/AVHRR sensors to detect large fires is discussed by Matson et al. (2), and its use with sub-pixel size fires, by Matson and Dozier (3).

MATERIALS AND METHODS

An operational scheme was devised at the Brazilian Space Institute (INPE/SCT) to record full 1.1 km resolution AVHRR images of the afternoon pass of the NOAA-9 satellite over central South America during the "burning" (dry) season in the Brazilian Amazon forest. The images were usually processed on the same night to detect large forest burnings, and by the following morning the geographical location of the main fires was available to state representatives of the Brazilian Environmental Institute (IBAMA/MA). Figure 1 depicts the area monitored, which corresponds approximately to the Brazilian Legal Amazon, with about $5 \cdot 10^6$ km². A description of this work and its results is found in Setzer et al. (4).

Forty-six images from July 15 to October 2, 1987, were analyzed and pixels in band three (3.55–3.93 µm) corresponding to an AVHRR radiometric temperature reading above 46°C were selected as burning sites by a digital nonsupervised clustering algorithm. These pixels were next examined in the visible channel (0.58–0.68 µm) to verify if a smoke plume was asso-

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ciated with each of them; the image was also visually screened to ascertain if any significant plumes existed without a "fire pixel". This process was accomplished by alternating in the CRT of the image-processing system the image only with the fire pixels and the image in the visible channel. Figures 2A and 2B correspond to such visible and infrared thematic and visible images for the area of the State of Rondônia. The number of pixels thus classified was obtained for the Brazilian Amazon as well as for the individual states of the region. The northernmost areas of the states of Amazonas and Para and the states of Roraima and Amapa were not examined because they were outside the satellite range as viewed by the direct receiving station which is located at about 25° S and 45° W. Figure 3 shows thousands of fires burning along an imaginary belt from Belém, at the mouth of the Amazon River, to Porto Velho, capital of the state of Rondônia, stressing the current geographical limits of forest conversion in Brazil.

Table 1 is a summary of the data obtained through 1987 and estimates of areas burned. The dates refer to the recordings of the high resolution 1.1 · 1.1 km AVHRR pixels, usually around 02:00 p.m. local time. The states of Acre and Maranhao had less frequent coverage because they appear at the far sides of the orbital path; other gaps in the data correspond to excessive cloudiness over the area of interest. The average number of fire pixels is the number of fire pixels registered in the images analyzed divided by the number of images; the total estimate of fire pixels is the average number of fire pixels multiplied by 80, the number of days that the burning season is assumed to have lasted based on Table 1.

In order to obtain the actual burned area some adjustments had to be made. First, some large fires may have lasted for more than one day and may have been registered twice by the satellite. Fieldwork information obtained by the researchers in northern Mato Grosso and Rondônia indicated that flames occur during relatively short periods in burnings associated with recent deforestation. The flames are over after about one hour for plots of 50 ha. Smoldering, however, may persist for many hours and even over one day when ambers are immersed in ashes or soil. Therefore, large burned areas of an AVHRR pixel size, or 100 ha, may release enough heat to sensitize the thermal sensor in the satellite even one day after the burning. This is easily proven by the Steffan-Boltzman equation, relating fourth power of absolute temperature to emitted energy. This effect was accounted for by dividing the number of fire pixels by 1.5, an assumed average duration of burnings, in days.

Second, in many cases the area actually burned, although smaller than a pixel, was depicted as a full pixel because of its high temperature. By comparing Landsat/TM and NOAA-9 images for selected areas also in northern Mato Grosso where burnings occurred, the authors found an overestimate of about 37% in the NOAA-9 images, and therefore another adjustment factor was used.

Finally, to obtain the corresponding burned areas, the adjusted pixel number was multiplied by 1.2, the area of a pixel in km^2 at nadir. Field experiments are currently in progress to determine more precise values for the above factors as well as their variation range. In our view the values used gave a conservative estimate. Several other effects could be considered, but we have no practical knowledge of these effects. For example, if a single pixel contains many fires, AVHRR will record only one, a situation that may occur in Amazon regions where a pattern of small properties exists and small plots are cleared, such as in the state of Rondônia. Also, in these areas, small fires may have ended by the time the satellite imaged the region, and

Table 1. Data summary for the 1987 burning (dry season).

	State*							
Date	AC	AM	PA	RO	MT	GO	MA	
July 15		13	15	219	459	46		
July 17		1	33		1145	230		
July 18		0	0		810	523		
July 19			155		760	746	324	
July 24	388	17	16	591	1539			
July 25	104			383	2129	222		
July 26		0	489	282	1247	273	39	
July 27		20	789	193	1391	522	30	
July 28		0	440		2125	710	493	
Aug. 03	50		167	363	1771	273		
Aug. 04		38	71	803	3042	615		
Aug. 05		39	567	776	1822	529		
Aug. 06			870		612	735	83	
Aug. 07			1002		1063	826	472	
Aug. 13		28	1434	2239	1811	503		
Aug. 15		32	1234	1121	1997	2562		
Aug. 16			165	2832	2258			
Aug. 21	119	29	120	2177	1854	262		
Aug. 22	315	35	6	1260	3314	617		
Aug. 23		25	461	933	2627	938	387	
Aug. 24		17	933	1758	3467	2304	488	
Aug. 30	69		180	457	307	948		
Aug. 31	11	24	290	519	1347	1519		
Sep. 01		35	767	853	3167	3541		
Sep. 02		3	2049	350	4743	3319	697	
Sep. 08	29	73	33	2515	1635	165		
Sep. 09	176	143	244	2371	3503	1166		
Sep. 17	296	0	4	500	1216	456		
Sep. 18		15	130	1250	1369	808		
Sep. 19		60	283	380	1298	572		
Sep. 20		6	767		1281	513	82	
Sep. 21		24	652		711			
Sep. 27				864	1561	188		
Sep. 28		0	33	12	1394	316		
Sep. 29		2	108	266	1294	1307	146	
Oct. 01		0	0		156	0		
Oct. 02		0	0		116	84		
No. of images	10	29	35	27	37	34	11	Total
No. of fire pixels	1557	679	14 507	26 267	62 341	28 338	3241	
Avg. no. fire pixels	155.7	23.4	414.5	972.9	1684.5	833.5	294.6	
80 (no. fire pixels)	12 456	1873	33 159	77 828	134 791	66 678	23 571	350 356
Adjust. fire pixels	6062	912	16 137	37 876	65 598	32 450	11 471	170 507
Burned areas, km^2	7274	1094	19 365	45 452	78 718	38 940	13 756	204 608

* Estimates for Rondônia may include some fires from Bolivia.
AC = Acre
AM = Amapa
PA = Para
RO = Rondônia
MT = Mato Grosso
GO = Gonias
MA = Maranhão

Table 2. Emissions estimates from biomass burnings in the Amazon during 1987.

Compound (million tons)	Emission estimates in Tg, or 10^{12} g
C (total)	520
CO_2	1700
CO	94
POC	4
EC	1
NO_x	1
NH_3	0.5
SO	0.4
K	0.4
TPM	6
O_3	9
CH_4	10
CH_3Cl	0.05

CO_2 emission from the text, after Seiler & Crutzen, (6); POC = Particulate Organic Carbon; EC = Elemental Carbon; SO = SO_2 + SO_4 (aerosol) + MSA (aerosol); TPM = Total Particulate Matter; CH_4 rate after Greenberg et al. (10); CH_3Cl rate after Crutzen et al. (11); other rates after Andrea et al. (9).

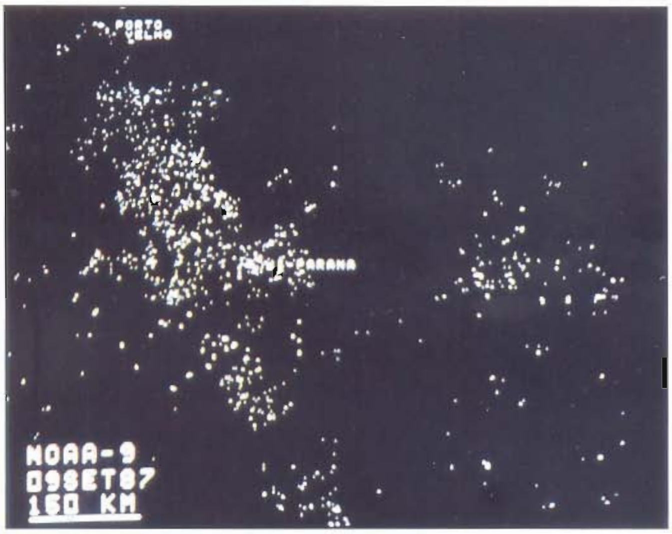

Figure 2A. Forest and agricultural burnings in the state of Rondonia, Brazil, on September 9, 1987. White dots correspond to pixels of channel three of the AVHRR sensor on board the NOAA-9 satellite which had temperatures above 46° C and were associated with fires. The BR-364 road through Ji-Parana and Porto Velho is of major importance in providing support for forest conversion. See Figure 2B for the associated smoke cloud.

Figure 2B. Smoke emissions from forest and agricultural burnings in the state of Rondônia, Brazil, on September 9, 1987. The yellow cloud shows the smoke produced by the individual fires depicted in Figure 2A. A combination of AVHRR channels one, two and three were used to produce the photo.

others may have not started. Another effect could result from very dense smoke clouds from fires in the region which may prevent AVHRR from detecting other fires. The area estimates consider pixels with nominal 1.2 km^2, what occurs only at nadir; pixels close to image borders may have over 10 km^2.

As shown in Table 1, the total estimate of areas burned in the Brazilian Amazonia Basin in 1987 is about 200 000 km^2 (20 million ha), i.e. close to five times the area of Switzerland. A knowledge of the percentage of this area that corresponds to recent forest conversion is necessary. This percentage varies regionally in the Amazon, from about 100% in the regions recently open to development, to a small percentage in regions developed many years ago or with predominant savanna-type (cerrado) vegetation. As no data exist, the authors suggest, based on limited field-work activities and examination of Landsat/TM images, about 40%, or 80 000 km^2 as a first guess. For the whole of the Amazon Tropical Forest the figure for forest conversion in 1987 must therefore increase since other countries, Bolivia for example, are also clearing new areas of the forest at increasing rates.

EMISSION ESTIMATES

Emissions of the 1987 burning into the atmosphere were by no means small. Press reports related that in the Amazon region and Central Brazil low visibility due to burnings that occurred hundreds of kilometers away closed airports for many days, caused boat accidents on rivers and also significant increases in respiratory diseases (4). Carbon monoxide concentrations in remote areas of the Pantanal, thousands of kilometers downwind from the main fires, increased by a factor of ten (5). The smoke clouds were so large that they were easily detected on the visible channel of images of the meteorological geostationary GOES satellite, and covered area of millions of km^2 (4). Figure 4 depicts such impressive smoke clouds. A preliminary estimate of the fire emissions was made as follows.

Based on the simple Seiler and Crutzen (6) method, a crude estimate of the amount of dry matter burned can be estimated from:

$M = A_i \cdot B_i \cdot a_i \cdot b_i$, for i=1 and 2, where
M = mass of dry matter burned, in g;
i = type of basic vegetation burned, where 1 is dense forest and 2 cerrado;
A_i = area of vegetation type i burned, in km^2;
B_i = average biomass of vegetation i, in $g \cdot km^{-2}$;
a_i = fraction of biomass over the soil for vegetation i; and,
b_i = % of above-ground biomass consumed by fire or combustion factor.

For biomass burning in dense forest and cerrado the following values were adopted, respectively: areas A_1 = 40% and A_2 = 60% of the total 200 000 km^2 burned; biomass content $B_1 = 22.6 \cdot 10^9 g \cdot m^{-2}$ (7) and $B_2 = 4.3 \cdot 10^9 g \cdot m^{-2}$(8); combustion factors b_1 = 0.6 (4), and b_2 = 0.75 (6). Therefore, the mass of dry matter burned in 1987 gives $M = 1.15 \cdot 10^{15}$ g.

According to Seiler and Crutzen (6), the associated emissions of carbon to the atmosphere should be 45% of the dry matter burned or $0.52 \cdot 10^{15}$ g. Based on relation rates for various gases and particulate matter found by Andrea et al. (9) in haze layers originating from biomass burning over Amazonia, and also on their mass relation, an estimate of emissions to the atmosphere was made and is presented in Table 2.

Again, these estimates are considered as preliminary and are based on many factors and assumptions that vary when one considers the extent of the area analyzed, the diversity of its vegetation, the physics and chemistry of the burnings, and the lack of field data. As for the total area estimate, we believe that the estimates are conservative.

Deforestation and accompanying burnings in the Amazon are probably occurring at exponential rates, which started in the early 1970s with the official policy to develop the region. Current yearly deforestation increases of 20% to 30% are accepted for the states of Amazonas, Mato Grosso, Pará, and Rondônia where most of deforestation takes place. If compared to a tentative evaluation of emissions for 1985 (12), the present estimate shows an increase of about 100% in the number of fires. An evaluation of deforestation for the Brazilian Amazon up to 1988, made with Landsat/TM satellite images (13), indicates that at least 350 000 km^2 of dense forest, excluding savannas, have been deforested. Considering that savanna areas in use within Amazonia also account for an area of the same magnitude, the total area subject to burnings in Brazilian Amazonia is probably over 700 000 km^2. The above estimate of 200 000 km^2 burned in 1987 is reasonable therefore, and indicates a burning cycle of about three years.

The 1987 emission estimate for particulate matter is similar in magnitude to that of a large volcanic eruption such as that of El Chichon in Mexico in 1982, which emitted an estimated $12 \cdot 10^{12}$ g of particles causing significant disturbances in the stratosphere which lasted many years (14). The burning emissions are in the lower troposphere, although some smoke clouds reach up to 4 km before starting to disperse horizontally. Considering that almost no rain occurs during the burning/dry season, the emissions enter the circulation of the

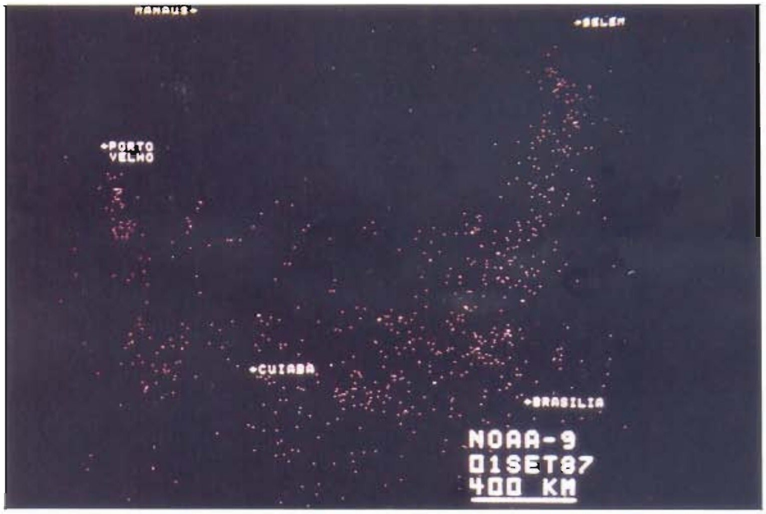

Figure 3. Same as Figure 2A, but showing the Brazilian Amazon region on September 1, 1987. The "belt" from Belem at the mouth of the Amazonas River to Porto Velho, in the state of Rondônia, shows the current limits of large-scale forest conversion.

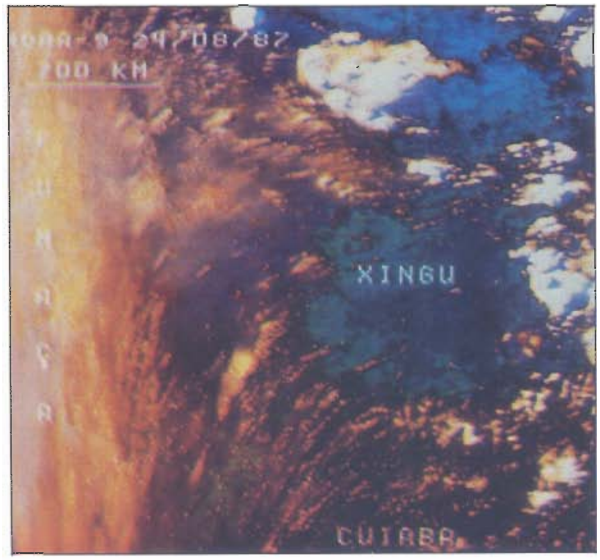

Figure 4. Same as Figure 2B, but for the state of Rondônia and northwest of Mato Grosso, on August 24, 1987. Yellow and purple colors correspond to smoke clouds produced by large fires. Note the clockwise anticyclonic pattern of the plumes, which flow southward to latitudes of 20°S; after which the flow diverts to the South Atlantic Ocean towards Antarctic latitudes (not seen in this image).

anticyclonic cell that prevails in Central Brazil during this period, and are transported to latitudes between 20° to 30°S over the Atlantic Ocean. In that region, increases in ozone tropospheric concentrations were reported as possibly linked with biomass burnings (15), as well as with tropospheric aerosols (16). Also in this region, as seen in meteorological satellite images, tropospheric air can be lifted to higher levels by convection associated to the sub-tropical jet stream, and which will eventually carry the emission to Antarctic latitudes as corroborated in wind charts. Biomass-burning emissions from the Amazon Basin are therefore a powerful source of carbon dioxide, and many atmospheric reactive gaseous compounds and aerosols that provide catalytic surfaces for photochemical reactions and these reactions could cause changes in the planet's climate and radiation absorption.

CONCLUSIONS

For the first time the amount and area of biomass burnings in the Brazilian Amazon Basin have been estimated. The result, 350 000 independent fires, possibly corresponding to 200 000 km^2 of area burned in various types of vegetation in the Brazilian Amazon in 1987 with emissions comparable to those of a large volcano are highly significant in regard to tropospheric chemistry on a world scale, air-pollution problems at the synoptic scale, as well as carbon dioxide, hydrological and radiation budget changes. With current growth in deforestation rates the burning phenomena and interactions with the atmosphere will increase, making control a major concern for the world community.

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