FIRE ESTIMATES IN SAVANNAS OF CENTRAL BRAZIL WITH THERMAL AVHRR/NOAA CALIBRATED BY TM/LANDSAT (*)

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ABSTRACT

"Cerrados" (savannas) in Brazil occupy $2.4 \times 10^6 km^2$, a third of which presumably burns every year associated to various agricultural uses, pasture renewal, and deforestation, causing environmental concerning. This paper examines a technique to estimate the number and extent of natural and man-caused fires in savanna regions of Central Brazil, based on AVHRR/NOAA band 3 (3.6-3.9um) thermal images with spatial calibration obtained from TM/Landsat digital color composites. Digital full 1.1km resolution AVHRR/NOAA-11 images from the June-September dry season in 1989 were analyzed to determine pixels with nominal radiometric temperature above a 315K threshold ("fire pixels"). For a TM/Landsat scene control area digitally processed, all the fires in the AVHRR images previous to the TM pass were counted and cumulatively located to allow a comparison of estimates. All fire pixels detected by AVHRR were located in fire scars of the TM image. The area of the fire pixels was about 43% larger than the area of the corresponding fire scars in the TM image. A correlation coefficient of $r^2=0.98$ was found between the areas measured on TM images and those of the fire pixels. Considering the common burning practices in Brazil this simple AVHRR image processing technique is proposed to evaluate on near-real time and at relative low cost the location, extent and frequency of biomass burning in the cerrados.

1. INTRODUCTION.

Savannas are "a tropical formation where the grass stratum is continuous and important, occasionally interrupted by trees and shrubs; the grass stratum is burnt annually, and the main growth patterns are closely associated with alternating wet and dry

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seasons" (Bourlière and Hadley, 1983). Savannas constitute a significant part of South America's vegetation, particularly in Central Brazil where they occupy about $2.4*10^6$ km^2. In this country, they are known as "cerrado(s)" and have been traditionally used for cattle grazing. Mechanized soy bean agriculture was introduced in cerrado areas of proper terrain and soil early in the 70's, followed by wheat more recently. Grasses of selected varieties have been also introduced to generate better pastures. (Azevedo and Adámoli, 1988).

For centuries fire has been employed by farmers and Indians in tropical cerrados, and the natural vegetation is adapted to fire regimes occurring every few years (Coutinho, 1980). Fire is the cheapest way to clear the vegetation during the dry season and the remaining ashes, rich in minerals, produce a short term fertilizing effect. On a long term basis, for most of the cerrados, fires conducted every year tend to deplete the soil and adversely affect its ecology (Coutinho, 1980). Emissions from such fires conducted on continental dimension scales are also a subject of concern with potential effects on the planet's atmosphere, climate, and biogeochemical cycles (Crutzen and Andreae, 1990). On a synoptic scale Kirchhoff et al. (1989), Setzer and Pereira (1991a), and Setzer et al. (1991) have demonstrated that emissions from fires in the Brazilian cerrado attain alarming proportions and effects.

Considering the intense deforestation and agricultural shifting that is taking place in the Brazilian cerrados alongside with traditional burning practices, there is a scientific and administrative need to quantify and understand fire in the cerrados. Since the area to be monitored is so large and no practical possibility exists to assess the fire occurrences through ground work or inventories, orbital remote sensing should be considered as a viable solution to produce such assessments.

Two kinds of satellite sensors can be considered for remote sensing of fires. High resolution TM/LANDSAT and HRV/SPOT (30m and 10m, respectively) are adequate to detect fire scars (Pereira and Setzer, 1991) but require excessive and expensive amounts of data for large areas as in the case of cerrados. Moreover, their temporal resolutions can not be used for daily coverages. The second kind, low resolution (1.1km) AVHRR/NOAA meteorological satellites, are adequate to detect active fires at the time of the satellite pass and cover large areas on a single image a few times every day at relatively low-cost images and image processing. The detection of biomass burning with AVHRR thermal channels was developed after the work of Matson and Dozier (1981) and Matson et al. (1984). The subject has been recently summarized and reviewed by Robinson (1991), and has been extensively tested and used operationally in Brazil (Kaufman et al., 1990; Pereira and Setzer, 1991; Setzer and Pereira, 1991a and 1991b).

The objective of the present work was the study of a technique to estimate the number and extent of natural and man-caused fires in savanna regions of Central Brazil, based on AVHRR/NOAA band 3 (3.6-3.9um) thermal images with spatial calibration obtained from TM/LANDSAT color composites.

2. STUDY AREA AND SATELLITE IMAGES

The study area selected has about 100,000km^{-2} and covers parts of the Central Brazilian states of Goiás (GO), and Tocantins (TO), being limited approximately by 11^{o}45'S to 14^{o}45'S and 48^{o}30'W to 51^{o}30'W. It contains most of the different units of cerrado physiognomy ("cerrado senso stricto", "campo cerrado", "campo sujo"), and has a high occurrence of fires as detected by AVHRR in the past (Setzer and Pereira, 1991b). This area was examined in AVHRR images which covers it in 300 columns and 300 lines.

Within this area, a sub-area equivalent to half of a TM/LANDSAT-5 (USGS/NOAA, 1984) frame with 185km x 185 km, was used to compare TM and AVHRR information about fires. It is located in the states of GO, MT and TO, between 12^{o}05'S to 13^{o}50'S, and 50^{o}00'W to 51^{o}40'W, corresponding to the satellite imaging orbit #223, subpoint #69. It contains mainly cerrados and campos cerrados. The image was recorded on 11/September/89 by INPE's station at Cuiabá, MT, and bands 3 (0.63-0.69um), 4 (0.76-0.90um) and 5 (1.55-1.75 um) were used in the analysis. The identification of fire scars in TM images is a relatively simple procedure resulting in precise information about fire locations and extent (Ponzoni et al., 1986; Pereira, 1988).

AVHRR (Advanced Very High Resolution Radiometer) full 1.1km nominal resolution images of the NOAA-11 satellite were recorded on real time by the HRPT (High Resolution Picture Transmission) INPE station located at Cachoeira Paulista, São Paulo, Brazil, at 22^{o}27'S and 45^{o}00'W (See Kidwell, 1985 and Needham, 1988 for additional information about AVHRR). Bands 1 (0.58-0.68um; visible light), 2 (0.725-1.10um; near-infrared) and 3 (3.55-3.93; mid-infrared) were recorded. Bands 1 and 2 and 3 were used for visual analysis and location of navigation points, and band 3 for fire detection. Table 1 presents the images recorded.

Table 1. AVHRR images used in the study

Month (1989)	Day	Equatorial longitude	crossing time(GMT)
June	14	307.3	17:18:38
July	13	307.1	17:20:25
August	11	306.9	17:21:49
September	05	296.6	18:04:41
September	06	299.2	17:54:08
September	07	301.9	17:43:05
September	08	304.5	17:33:01
September	10	309.8	17:11:54
October	08	307.7	17:21:08

Fires in the AVHRR images for the region of interest were detected using the normal procedures for the operational, fire watch program of INPE described by Setzer and Pereira (1991c) also in this volume.

The fire information from the AVHRR and TM images was associated to a cartographic base digitized from the vegetation map of Brazil in the scale of 1:5,000,000 (IBGE/IBDF,1988). The image processing was done in the SITIM interactive system and the overlap of fires and the vegetation map in a GIS-Geographical Information System also developed at INPE (ENGESPAÇO/INPE, 1990).

3. FIRE DATA IN AVHRR/NOAA-11

As shown by Pereira (1988) or Pereira and Setzer (1991), fires detected by AVHRR on board NOAA-9 were concentrated in the first (and hottest) ten levels of digital counts in the band 3 images processed with 256 count levels (8 most significant bits). The fires actually peaked in the 10th level and not in the first as one would expect when considering the saturation limit of 320K for the AVHRR channel 3 and also the theoretical considerations related to the energy emitted by fires (Robinson, 1991).

Instead of NOAA-9, this work used NOAA-11, the operational satellite for early afternoon passes available when the images were recorded in 1989. Variations in data from different satellites exist mainly as a result of changes in instrumental design, calibration, and decay with time. Therefore, a preliminary exam was conducted to verify the characteristics of fires in the pixels of AVHRR channel 3 on board NOAA-11.

Full 1.1km resolution AVHRR/NOAA-11 images of 14/June, 13/July, 11/August, 08/September and 08/October were used in the test. They span the dry (burning) season in the cerrados, and represent a wide range of sun-target-satellite angles. They were navigated to the accuracy of three pixels and processed as described elsewhere in this publication (Setzer and Pereira, 1991c). The histogram of count levels for the images (Figure 1), however, showed that the peak of fire pixels found in NOAA-9 images had a shift of one count in the NOAA-11 images, including eleven count levels (320 to 315 K), and not ten as in the case of NOAA-9.

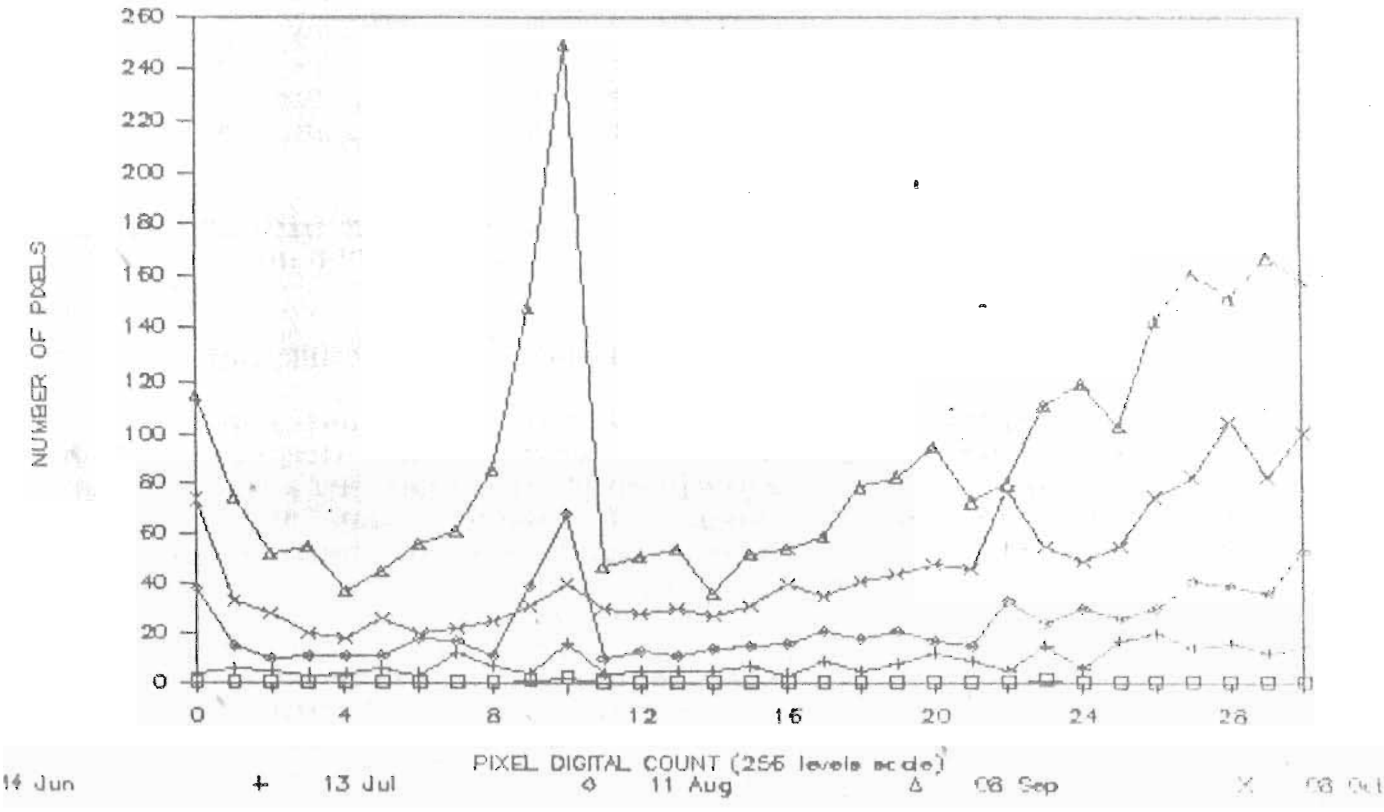

Figure 1. Histogram of "fire" pixels in five AVHRR/NOAA-11 images during 1989. Counts 0 and 10 correspond to 320K and 315K nominal ground radiometric temperatures, respectively.

Figure 2 shows an example of fire pixels on a print out with digital counts from a section of the AVHRR image recorded 08/September. This case is also referred to on Table 2, with a TM fire scar of $17.06km^2$, and was located at 13°12'S and 50°41'W. The hottest pixel had a count of 5 and the minimum temperature considered had the count of 10.

107	112	113	108	102	110	114	116	109	99	102	111	119
104	108	116	111	103	109	111	109	99	105	113	122	127
97	99	102	93	100	112	99	95	103	117	125	126	120
93	91	90	89	9	10	10	41	75	101	123	124	123
91	87	112	22	10	10	10	10	10	8	94	117	105
94	103	9	10	10	9	10	10	72	77	120	126	129
102	95	15	5	86	91	83	82	83	99	122	123	124
107	92	82	108	116	96	88	85	83	95	118	124	125
106	107	113	112	92	89	91	91	100	110	117	113	116
95	92	88	87	88	89	88	99	117	120	123	118	109

Figure 2. Digital counts of fire pixels (inside in the line) in an AVHRR/NOAA-11 image.

4. CALIBRATION BETWEEN LANDSAT/TM AND AVHRR/NOAA-11 DATA

A comparison of TM and AVHRR fire data in the same region was done to obtain calibration factors between these two different sensors. The TM image of 11/September/89 on the approximate scale of 1:50,000 was assumed to provide the ground truth data concerning the location and area extent for fires in the cerrados. It was digitally classified in full resolution using the non-parametric supervised parallelepiped method. Following the experience of Ponzoni et al. (1986) and Pereira (1988) to identify fire scars on TM images, the following color composition was used: blue for band 3, green for band 4 and red for band 5. With this composition the identification of fire scars was very clear, allowing an appropriate training of the supervised classifier algorithm. The algorithm was then expanded to the TM image, showing all fire scars. The area of the fire scars was estimated multiplying the number of pixels in each fire scar by $0.0009km^2$, the area of a TM pixel. In the case of AVHRR fire pixels, the area was obtained multiplying the number of pixels by $1.2km^2$, the nominal area of an AVHRR pixel at nadir.

The overlap in the GIS of the TM classified image with the fire pixels in the various AVHRR images of preceding dates, and also with the digitized vegetation map, allowed the comparison of the fires detected by the satellites.

For all thirty-seven sets of fire pixels detected by AVHRR/NOAA-11, without exceptions, a corresponding fire scar was found in the TM image within limits of navigation errors. Some fire scars in the TM image had no corresponding fire pixels, what was interpreted as a consequence of the probability that the TM image also had fire scars from days when AVHRR images were not examined, as on 09/September and before 05/September. About 35% of the fire scars in the TM image had no AVHRR corresponding fire pixels, possibly also resulting from the consequence just mentioned.

The relation between areas of individual fire scars on TM and those of the corresponding AVHRR sets of fire pixels was obtained from a simple regression study. Fires detected by AVHRR were located in the TM image, and those closer than 3km to two or more TM fire scars were disregarded to avoid errors introduced by lack of precision in the AVHRR image navigation. Eleven fire events were thus selected and had their area measured automatically in the TM and AVHRR images based on the number of pixels, respectively. The areas of the fire scars in the TM image and of the corresponding sets of fire pixels in the AVHRR are presented in Table 2 below.

Table 2. Areas (km^2) of fires in TM and AVHRR images.

TM	AVHRR	REGRESSION
0.070	2.4	-0.4
0.114	1.2	-0.4
0.874	2.4	0.8
1.420	1.2	1.6
2.426	2.4	3.1
2.555	3.6	3.3
6.020	8.5	8.4
7.072	13.3	10.0
14.886	15.7	21.6
17.060	19.4	24.9
50.531	78.7	74.8

The linear regression coefficient for the areas of these eleven points is $r^2=0.98$, and the linear equation that fits them, in units in km^2, is given by:

$$AVHRRarea = -0.538 + 1.49*TMarea$$

Figure 3 shows this regression line relating the area of the

TM fire scars and the corresponding AVHRR sets of fire pixels. Table 2 also shows what AVHRR areas are obtained when the regression equation found is applied to the TM values. For the eleven cases, AVHRR overestimated the area burned by about 43%. Except for two cases, AVHRR overestimated the area of the fires, therefore indicating that in general only fractions of fire pixels were actually on fire at the time AVHRR scanned the region, and that the fires presumably died soon after the AVHRR overpass.

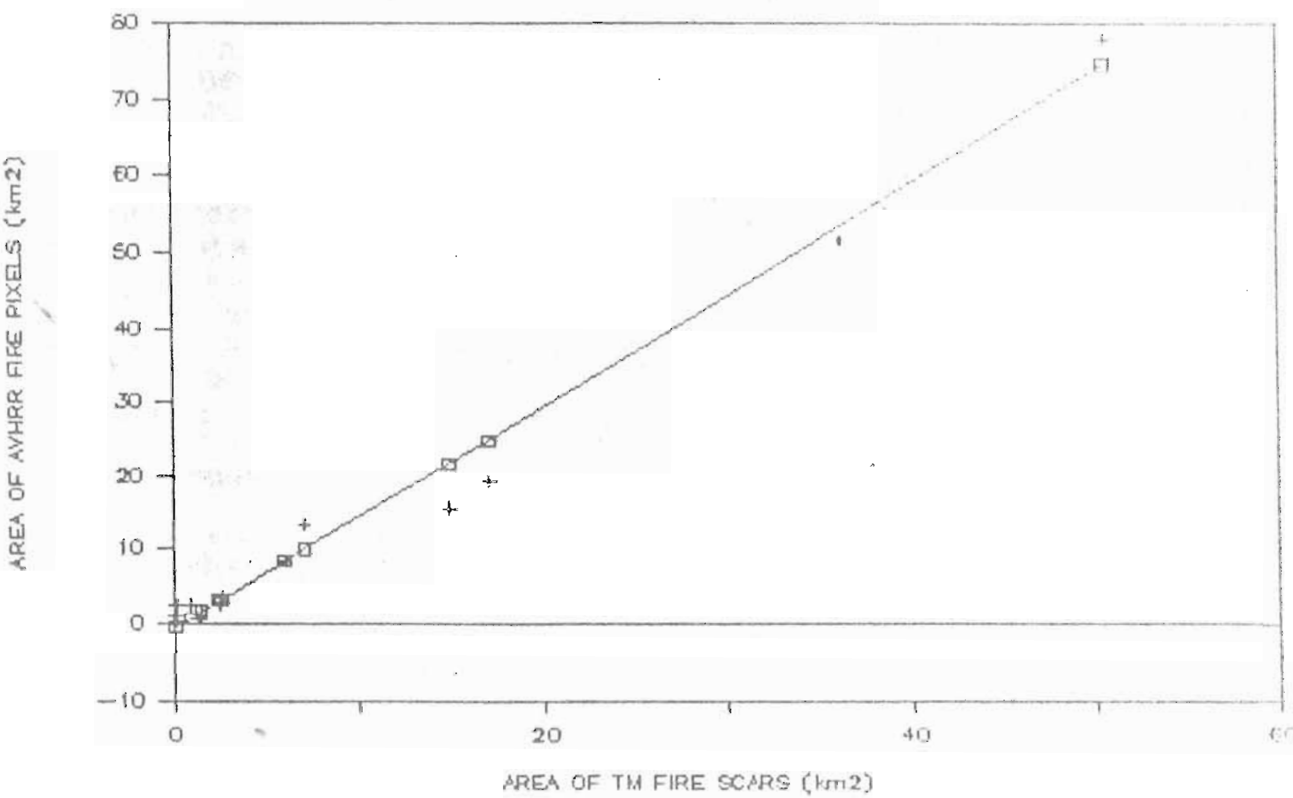

Figure 3. Regression line between AVHRR fire pixels and TM fire scars.

The estimate of areas of fires from AVHRR fire pixels is complex, and many factors can either increase or reduce the estimates in relation to the area actually burned. As shown by Pereira et al. (1990) for the 1988 great fire at the Emas National Park, GO, when fires in the cerrado spread uncontrolled, AVHRR fire pixels corresponded only to 13% of the area burned measured on a TM image. In that case, AVHRR only provided once a day an instantaneous picture of fires that spread with speed of many kilometers per day. AVHRR fire pixels will also underestimate the area burned if before the overpass the fire stopped or if the ground had enough time to cool. Another effect that reduces area estimates from fire pixels is the presence of smoke clouds. If dense enough, smoke clouds prevent AVHRR from detecting fires downwind or even at its very source depending on the satellite viewing geometry in relation to the fire and the smoke emissions. Regular meteorological clouds could also prevent detection of fires, but this has not been the case. Most fires do not start naturally; they are lit by humans to renew pastures or just to clear wanted vegetation. Under these conditions, fires are seldom started on cloudy or partly cloudy skies, what would reduce significantly the combustion efficiency. And finally, the off-nadir position of AVHRR fire pixels also has to be considered. A 1.2 km^2 nadir pixels can become 10km^2 when close to the border of the image, causing differences in area estimates.

Despite the existing limitations the authors believe AVHRR has a strong potential for fire assessment in large areas as the Brazilian cerrados, where no data about fires is available. The data presented in this paper shows that AVHRR can effectively detect most of the fires, and therefore can be used in operational activities to identify, locate and control the fires. In terms of area estimates, if no major uncontrolled fires occur, simple regression equations may give a reasonable estimate of the area burned. Considering that thousands of fires occur in most days of the dry/burning season, such regression equations should produce enough accurate results.

Intensive study of AVHRR fire pixels in relation to TM ground truth in the cerrados is continuing and the authors expect to improve the method to estimate areas burned with AVHRR presented above. With new satellite sensors being planned specifically for fire detection, and with the experience and data being obtained, fire monitoring from space should became a reality in the not distant future.

5. CONCLUSIONS

Initial results are presented relating 1.1km resolution "fire pixels" in AVHRR/NOAA-11 thermal Band 3 (3.6-3.9um) to corresponding fire scars on 30m resolution TM/LANDSAT-5 images. A study area of about half of a TM image was selected in the savannas ("cerrados") of Central Brazil, where fire is used extensively. AVHRR images for 5 days preceding the TM image were analyzed.

Tests to characterize fire pixels indicated that fires are recorded by band 3 as having a nominal radiometric temperature in the range of 315K to 320K, peaking in the lower limit.

To all 37 sets of fire pixels detected in 5 AVHRR images, a corresponding fire scar in the TM image was also found within the AVHRR navigation precision of 3km. About 35% of the fire scars on the TM image had no AVHRR fire pixels associated, possibly because many fires were missed in the days AVHRR images were not examined.

For eleven sets of AVHRR fire pixels where no doubts existed about their precise association to TM fire scars, a comparison of the areas of the fires was made. In the average, AVHRR overestimated the area burned in about 43%. The correlation coefficient between the areas of the sets of fire pixels and the corresponding TM fire scars was $r^2=0.98$.

AVHRR band 3 is an adequate tool to detect and locate fires over large cerrado areas where no reliable fire assessments exist. To estimate the areas burned, AVHRR data can produce approximations provided that previous calibration with ground data exists and no widespread fires take place.

Research to improve the statistics of the above findings is being conducted in larger cerrado areas. If future satellite sensors are properly designed for fire detection, orbital monitoring of fires may became a reality and fire regimes in the planet will be understood.

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7. REFERENCES

AZEVEDO, L.G.; ADÁMOLI, J. 1988. Avaliação agroecológica dos recursos naturais da região dos cerrados. In: 6th SIMP. SOBRE O CERRADO, Brasilia, DF, 1982. Proceedings. EMBRAPA-CPAC, Planaltina, DF, pp. 729-761.

BOURLIERE, F. J.; HADLEY, M. 1983. Present-day savannas: an overview. In: Bourliere, F. (ed.), Tropical savannas. Elsevier, Amsterdam, pp. 1-17. (Ecosystems of the World, 13).

COUTINHO, L.M. 1980. As queimadas e seu papel ecológico. Brasil Florestal, sv(44):7-23.

CRUTZEN, P.J.; ANDREAE, M.O. 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science, 250:1669-1678.

ENGESPAÇO/INPE. 1990. Sistema de Informações Geográficas (versão 2.3). Manual do usuário. INPE, São José dos Campos, SP.

IBGE/IBDF. 1988. Mapa de vegetação do Brasil. IBGE, Rio de Janeiro, RJ.

KAUFMAN, Y.J.; SETZER, A.W.; JUSTICE, C.;TUCKER, C.J.; PEREIRA, M.C.; FUNG, I. 1990. Remote sensing of biomass burning in the tropics. In: Goldammer, J.G. (ed.), Fire in the tropical biota: ecosystem processes and global challenges. Springer-Verlag, Berlin Heidelberg, 1990, pp. 371-399. (Ecological Studies, 84).

KIDWELL, K.B. 1985. NOAA polar orbiter data (TIROS-N, NOAA-6, NOAA-7, NOAA-8 and NOAA-9) user guide. NOAA, Washington, DC, 98pp.

KIRCHHOFF, V.W.J.H.; SETZER, A.W.; PEREIRA, M.C. 1989. Biomass burning in Amazonia: seasonal effcts on atmospheric O_3 and CO. Geophys. Res. Letters, 16(5):469-472.

MATSON, M.; DOZIER, J. 1981. Identification of subresolution high temperature sources using a thermal IR sensor. Photogramm. Engin. and Remote Sensing, 47(9):1311-1318.

MATSON, M.; SCHNEIDER, S.R.; ALDRIDGE, B.; SATCHWELL, B. 1984. Fire detection using the NOAA-series satellites. NOAA, Washington, DC, 34pp. (NOAA Techinical Report NESDIS, 7).

NEEDHAM, B.H. AVHRR: next geration AVHRR - AMRIR. 1988. Photogramm. Engin. and Remote Sensing, 54(9):1333-1335.

PEREIRA, M.C. 1988. Detecção, monitoramento e análise de alguns efeitos ambientais de queimadas na Amazônia através da utilização de imagens dos satélites NOAA e Landsat, e dados de aronave. INPE, São José dos Campos, SP, 268pp. (INPE-4503-TDL/326).

PEREIRA, M.C.; AMARAL, S.; ZERBINI, N.J.; SETZER, A.W. 1990. Estimativa da área total queimada no Parque Nacional das Emas com o uso de imagens da banda 3 do AVHRR: comparação com estimativas do TM-Landsat. In: 6th SIMP.BRAS.SENSOR.REMOTO, Manaus, AM, 1990. Proceedings. INPE ,São José dos Campos, SP, 1990, vol. 2, pp. 302-310.

PEREIRA, M.C.;SETZER, A.W.1991. Spectral characterization of forest fires in NOAA/AVHRR images. Submited for publication in Int. J. Remote Sensing.

PONZONI, F.J.; LEE, D.C.L.; HERNANDEZ FILHO, P. 1986. Avaliação da área queimada e da regeneração da vegetação afetada pelo fogo na Parque Nacional de Brasilia através de dados TM/Landsat. In: 4th SIMP.BRAS.SENSOR.REMOTO, Gramado, RS, 1986. Proceedings. INPE, São José dos Campos, SP, vol. 1, pp. 615-621.

ROBINSON, J.M. 1991. Fire from space: Global fire evaluation using infrared remote sensing. Int. J. Remote Sensing, 12(1):3-24.

SETZER, A.W.; PEREIRA, M.C. 1991a. Amazonia biomass burning in 1987 and an estimate of their tropospheric emissions. Ambio, 20(1):19-22.

SETZER, A.W.; PEREIRA, M.C.1991b. Relatório projeto "SEQE" - ano 1988. INPE, São José dos Campos, SP. In press.

SETZER, A.W.; PEREIRA, M.C. 1991c. Submited for publication in Proceedings of 24th INTERNAT. SYMP. REMOTE SENSING OF ENVIRONMENT, Rio de Janeiro, RJ, 27-31 May 1991.

SETZER, A.W.; KIRCHHOFF, V.W.J.H.; PEREIRA, M.C., 1991. Ozone concentrations in the Brazilian Amazonia during BASE-A. Chapman Conference, 1990. J. Levine (ed.),Proceedings: Global Biomass Burning. In press.

USGS/NOAA. 1984. Landsat 4 data users handbook. USGS, Alexandria, VA.