Remote Sensing Reviews, 1994, Vol. 10, pp. 91–103
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Satellite Studies of Biomass Burning in Amazonia—Some Practical Aspects

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ABSTRACT

Remote sensing from space is the only technique that can be used operationally to detect, monitor and map biomass burning of tropical forests on large or global scales. However, high and low resolution imagery from existing satellites present many limitations in such studies. This paper discusses some of these limitations based on case studies in the tropical forests of Amazonia. Results showed that Thematic Mapper (TM/Landsat) images provide estimates of the area burned in association with new deforestation, but because of cloud cover and low frequency of acquisition, are limited in indicating the total extent of fire activity. Advanced Very High Resolution Radiometer (AVHRR/NOAA) images detect fires on a daily basis and are suitable for real-time operational use to identify and locate fires, but are of limited value for estimating the area burned or the fire temperature.

INTRODUCTION

Biomass burning is directly related to many environmental concerns such as atmospheric pollution, soil depletion and vegetation removal. Its emissions result mainly from human actions (Crutzen and Andrea, 1990) and their effects play significant roles in changes of local and global climate and in biogeochemical cycles (Andreae, 1991). Although a world-wide phenomena, biomass burning takes place mostly in the tropics and in boreal forests, where little or no information exists about occurrences of fire. To overcome this limitation methodologies for global monitoring products obtained from satellites are being considered (IGBP, 1990). Future plans involve a combination of satellite fire detection and geographical information systems containing vegetation data bases to evaluate atmospheric emissions and vegetation changes (Malingreau, 1990 and 1993).

The Amazon forest has been the subject of particularly intense fire activity in the last decades (Helfert and Lulla, 1990; Kaufman et al., 1990; Setzer and Pereira, 1991a) in association with deforestation practices (Fearnside, 1990; Uhl and Kaufman, 1990). Fire in Amazonia, as in most of South America, is also extensively used to prevent vegetation growth and to "renew" pastures in all types of soils and relief, regardless of long-term damaging environmental effects. Fires in the Amazon forests normally do not occur or spread naturally. Apparently, the only reference to such a case was in 1912 (Koch–Greenberg, 1917, quoted by Sternberg, 1987); 1912 was an extremely dry year, with record low river levels in the Amazonas River basin, creating favourable conditions for fires. During September 1991, in a very dry season, the authors documented various fire fronts of many kilometers each advancing inside natural forests in the central part of the state of Mato Grosso, Brazil. These fires burned only the layer of dead organic matter above the ground and the lower canopies; standing and tall trees were not affected by these fires, which spread from "controlled" fires in the region. Fires in the Amazon forest are normally associated with its conversion and are limited to the area where the forest was cut. On average, about 44 days after the forest and lower vegetation has been cut fire is used to burn all the biomass possible (Fearnside, 1990). Since large trunks are not much affected by the first fire, the process is repeated for a few years until the original biomass is burned. Recent in-situ measurements of gases and particulate matter emissions from fires in Amazonia have been reported by Kaufman et al. (1992) and Ward et al. (1992); their effects on synoptic scale on atmospheric chemistry were measured also by Andrea et al. (1988), Kirchhoff (1991), and Artaxo et al. (1993), providing evidence of the continental hazards resulting from biomass burning in Amazonia.

Techniques for detecting active fires and fire scars in this tropical forest environment have been developed since the pioneering work of Matson et al. (1984) in the case of images from the Advanced Very High Resolution (AVHRR) onboard the NOAA-series satellites. More recently, Pereira and Setzer (1993a) reported a methodology for fire detection using channel 3 (3.55–3.95 μm) which has been used since 1987 in Brazil in a near real-time operational program to combat fires (Setzer and Pereira, 1991b; Setzer et al., 1992). The AVHRR was not designed for fire studies but has some characteristics (Kidwell, 1991) which allow its use for this purpose on a limited basis: it has three thermal channels; it covers wide regions in each image (the scanner sweeps 110.8 degrees, what from its sun-synchronous orbit at $\sim$ 833 km results in a ground swath of 2925 km); and any region in the globe is covered at least four times daily by the two NOAA satellites maintained operationally.

High resolution satellite images like TM/Landsat and HRV/SPOT, with 30 and 10 meters resolution respectively, provide spectral information to map fire scars—see Pereira and Setzer (1993b) for a summary of studies made in the last two decades. However, three limitations prevent their use for operational, real-time, and continuous monitoring and detection of biomass burning. First, the area covered in each image, on the order of 30,000 km^2 for TM and 3,600 km^2 for SPOT, is too small in terms of global or continental scales, demanding hundreds of images at high cost and associated processing difficulties. Second, the interval between successive images of the same location is about two weeks, too long for monitoring changes that take place on a daily basis. Thirdly, cloud cover combined with the low overpass rate further restricts the time interval between acquisition of useful images.

The use of satellite imagery in fire and fire ecology studies in the Amazon region has its limitations and these are not always considered when the satellite products are used or suggested. In the following sections we discuss some of the limitations based on case and field studies conducted in recent years.

A TM/LANDSAT ESTIMATE OF AREAS BURNED

Six TM (path/row 227/67) and one Multi-Spectral Scanner-MSS (path/row 224/67) Landsat images from different years for the region of the city of Alta Floresta, in the northern part of the state of the Mato Grosso, Brazil, were analyzed to map the extent of deforestation and associated biomass burning activity. The years included in this study were 1978 (MSS image), and 1984–1989 (TM images), with their exact dates shown in Table 1. The 1978 image (Figure 1) shows the beginning of deforestation in the area, when the city (9°35′S and 56°05′W) was being established and the first roads were opened in the tropical forest. The 1989 image (Figure 2) shows the same area after considerable development and deforestation took place. A map locating the study area and a photograph showing local fire scars can be found in Pereira and Setzer (1993b). A visualization of the context of deforestation for this area in relation to the large-scale Amazon deforestation for the period of 1978 to 1988 can be found in Skole and Tucker (1993).

Only two main classes were identified in all seven images for the purpose of biomass burning analysis: deforested areas other than fire scars, and fire scars. Total deforested area for each data therefore is the sum of the areas mapped in the two classes for the corresponding image. The classification made was based on the previous experience of the authors in the detection of fire scars in the same region, which showed that fire scars are much better identified in TM channel 4 (Pereira and Setzer, 1993b) and MSS channel 6. The channels used in the classification of the TM images were 3 (0.63–0.69 μm), 4 (0.76–0.90 μm), and 5 (1.55–1.75 μm); in the MSS image the channels were 5 (0.6–0.7 μm), 6 (0.7–0.8 μm), and 7 (0.8–1.1 μm). Image interpretation for the years of 1978, 1984, 1987, 1988, and 1989, was done manually with visual identification of the two classes of interest. Colour composite photographs in the scale of 1 : 250,000 were used, and the resulting maps were digitized in a geographical information system (GIS). For 1985 and 1986 automatic digital classification of the raw images was made using a maximum likelihood algorithm with TM channels 3, 4 and 5 (Pereira and Setzer, 1993b). Results of the analysis are summarized in Table 1.

The dry season in the region of study usually covers the period June to October, with biomass burning peaking between mid-August and mid-September. In order to include as much burned area as possible in the analysis the images selected for the study were those acquired as close as possible to the end of the dry/"burning" season, around late October or early November. The imagery was obtained from the archive of Landsat images kept by Brazilian National Space Institute (INPE), which usually records and stores all passes over Brazil. However, because of cloud cover in most of the images in the archive, no images were found in the period wanted. The dates of available images, listed in Table 1, varied from 27/June in 1986 to 20/September in 1988. This limitation in tim-

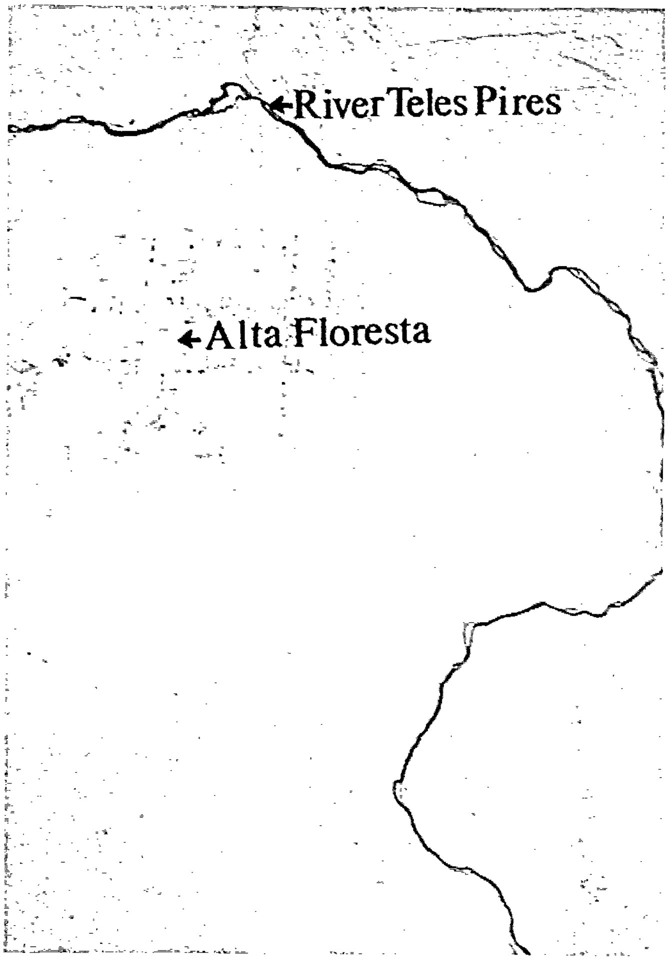

FIGURE 1 Landsat-MSS image for 31/July/1978 showing the beginning of deforestation in the region of Alta Floresta, MT, Brazil. 209 ha of fire-scars are shown in dark and grey tones, covering 74% of the 281 ha of the deforested areas. The image boundaries are 9°30′S to 10°30′W and 55°30′W to 56°30′W. The distance between the two arrows is 30 km. Colour processing with MSS channels 5, 6 and 7 depicted in yellow, cian, and magenta, respectively. (See color plate VIII at the back of the journal.)

ing should be expected in any set of high resolution imagery for tropical forests and exemplifies restrictions in a time study of biomass burning using such imagery. In addition, year-to-year variations in weather conditions, particularly in rain amount and distribution, introduce further limitations in the analysis of the images. For instance, in the image of 08/Aug/84, a wet year, only 3% of the deforested area was covered by fire scars, whilst on 11/Aug/85, a dry year, fire scars spread to 40% of the deforestation in the scene. For 1984, as well as for other years, no later images were found to check if the fire activity was just postponed in the same year or never took place.

FIGURE 2 Landsat-TM image for 22/August/1989 showing the same region of Figure 1, but after significant deforestation. 1284 ha of fire-scars are shown in dark and purple tones, covering 50% of the 2,588 ha of the deforested areas. The distance between the arrows is 30 km. Colour processing with TM channels 3, 4, and 5 depicted in blue, green, and red, respectively. (See color plate IX at the back of the journal.)

Despite these limitations, important observations about biomass burning were made from the high resolution images analyzed. First, it was possible to estimate the area of new fallen forest burned between any two years based on their respective images. Deforestation usually occurs as early as possible in the dry season, so more time is available for drying the fallen vegetation before burning it. As a result, images of the central Brazilian Amazonia obtained from late June onwards tend to show nearly all the deforestation for the year. Since all new deforested areas are burned, the area of increased deforestation for each year corresponds to the area of primary forest that was burned in that year. Table 1

TABLE 1
Areas of deforestation and fire-scars in Landsat images (ha units). Values in column "Total Deforestation" are the sum of those in columns "Area of Fire Scars Only" and "Deforestation Without Fire-Scars"; the last column is the ratio of columns "Area of Fire-Scars Only" and "Increase on Deforestation Area".

Dates of Landsat Images	Area of Fire-Scars Only, ha	Deforestat. Without Fire Scars, ha	Total Deforestat. Area, ha	Increase in Deforestat. Area, ha	Fire-Scar Area % of Total Defor.	Ratio of Fire-Scar/ Defor. Incr.
31-Jul-78	209	72	281	281	74	0.7
8-Aug-84	38	1109	1147	866	3	0.1
11-Aug-85	510	756	1266	119	40	4.3
27-Jun-86	0	1393	1393	127	0	—
16-Jul-87	97	1877	1974	581	5	0.2
20-Sep-88	1500	854	2354	380	64	3.9
22-Aug-89	1284	1304	2588	234	50	5.5

shows that this area had a peak in the burning of fallen primary forest in 1987, when 581 ha were deforested, a 4.6-fold increase in relation to the two previous years and also to the average of the 1979–1986 period.

Table 1 also shows that the total area burned in each year, including therefore new deforestation and reburning, tends to be higher towards the end of the dry season and its extent depends basically on how dry the season was. In 1989, by 22/August, 50% of all the deforested area in the region (2,588 ha) was covered by fire scars (1,284 ha), and on 20/September/88, of all the deforested area (2,354 ha), 64% (1,500 ha) consisted of fire scars. The 74% figure for fire scars on 31/July/1978 was probably a consequence of intense fire activity at the initial phase of forest clearing and development of the region. In 1988 and 1989 the burning of new deforested areas (380 and 234 ha, respectively) was just a fraction of the total area burned (1,500 and 1,284 ha, respectively), as shown in the last column of Table 1. Excluding 1984, 1986, and 1987 (early acquisition dates), this set of data shows that for the area analyzed, on average, every year at least 60% of the area of converted forests was burned following the common spread practice of fire use in the Amazon region. If the dry season is considered until its end, at late October for this region, this figure should increase even further. In addition, if the results of this region are extrapolated to the areas of deforestation in Amazonia (e.g., Skole and Tucker, 1993) the concerns of global change and local environmental problems associated with biomass burning become clear.

AVHRR/NOAA DETECTION OF FIRES

AVHRR images of the NOAA-series satellites have been used for operational fire detection in Amazonia since 1987 (Setzer et al., 1992). The technique is based mainly on full resolution (1.1 km) channel 3 (3.55–3.93 μm) data processed in near real-time (Pereira and Setzer, 1993a). The geographical locations of detected fires are then sent by telex to the users. During the peak of fire activity many thousands fires are detected daily (Setzer and Pereira, 1991a; Setzer et al.,

1992) and are almost all caused by humans. Field verification by the authors of many dozens of fires every year in the Brazilian Amazonia detected with this technique indicated no misidentification of fires; over 98% success in locating fires has been reported by other users of the products in various parts of Brazil (Setzer et al., 1992). Another type of verification consisted of controlled fires started at pre-determined sites and under specific conditions for research investigations. AVHRR images were then examined to analyze how these fires were detected. The following text reports these results and some of the limitations found in the current channel 3 detection method.

The first controlled burning took place on 04/September/1989 at a deforestation site about 50 km south of the city of Alta Floresta, at 10°30'S and 56°24'W. The same fire was also used for in-situ and airborne measurements to evaluate emissions from biomass burning (Kaufman et al., 1992). The size of the area burned was about 3.1 km by 0.8 km (2.4 km^2), and the fire was started about 40 minutes before the afternoon overpass of NOAA-11 (66.1°W equatorial crossing at 18:15 GMT, 14:15 local time). Flames were present over most of the site during this overpass but had disappeared before the next recorded NOAA images. The fire was started by people with torches at many places, almost simultaneously, and with the help of the wind spread to the whole site in about 30 minutes. After three hours just minor flaming activity was occurring and it was possible to enter the site again. Unfortunately, due to limitations of the AVHRR recording station, not all channels were recorded for all images.

The controlled fire was located in the image from its geographical coordinates through a navigation algorithm with a precision of one pixel. The origin of a noticeable smoke plume coincided with the location of the fire found in the image and corroborated its location (see Figure 3). No geometric or radiometric corrections were made, thus allowing examination of pixel counts as registered by the AVHRR sensors. The fire was first detected in the NOAA-11 AVHRR channel 3 image as six contiguous hot, or "fire-pixels", but it was not evident in channels 1 and 2, the only other channels recorded during this overpass (see Figure 4a). Considering the NOAA satellites at 833 km of altitude and the channel 3 instantaneous field-of-view as 0.00151 miliradians (Kidwell, 1991), the nadir pixels have a ground diameter of 1.26 km and a surface of 1.24 km^2; overlap of any pixel by contiguous pixels close to nadir is $\sim 63\%$ because the along-scan distance between pixels is 0.79 km and the along-track distance is 1.079 km (Setzer and Malingreau, 1993). This fire was centered in image column 260, at a corresponding scan view-angle of $\sim 41°$, where pixels become ellipses with axes of 2.51 km and 1.73 km, covering a surface of 3.4 km^2. At such large off-nadir angles the overlap by contiguous pixels also increases significantly, with along-scan and along-track distances between neighbour pixels of 1.57 km and 1.079 km, respectively (Setzer and Malingreau, 1993); as a consequence, a large and intense fire like this one is likely to be detected simultaneously in many neighbouring pixels giving an erroneous indication of its size. A first calibration, without considering pixel overlapping, indicates the fire to have an area equal to six times the pixel size, ~ 20 km^2, or about 8.5 times larger than its actual size. This exaggerated size is reduced if the distance between the centers of the fire-pixels is used in-

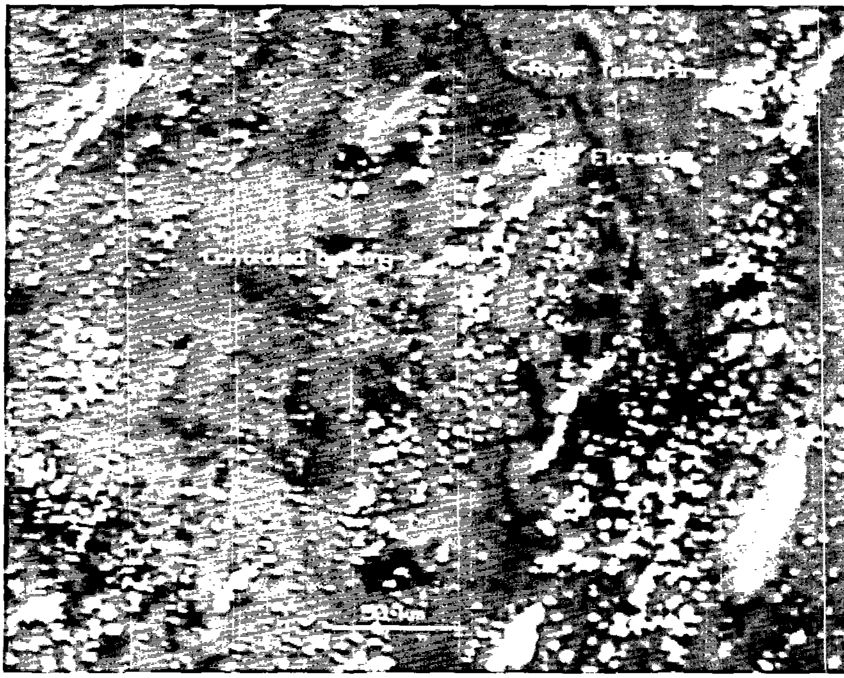

FIGURE 3 NOAA-11/AVHRR image for 04/September/1989 showing channel 3 fire-pixels (in red) and smoke plumes in the region of Alta Floresta, MT, Brazil. The controlled fire has six fire-pixels at an AVHRR off-nadir scan-angle of ~ 41°. (See color plate X at the back of the journal.)

stead, resulting in an area of 3.1 km by 2.2 km, or ~ 6.8 km^2. The digital counts of the fire-pixels in this AVHRR channel 3 image were 7 or 10 on a 256 level scale (see Figure 4a). The AVHRR has inverted scales for the thermal channels and these values corresponded to 321.0 K and 321.7 K, respectively, when transformed to temperature based on the on-board AVHRR calibration data. These temperatures certainly do not corresponded to the temperature at the site, which was at least on the order of 800 K in the flaming parts, therefore well above the saturation limit of 321.8 K (count 0). Pixels surrounding the fire-pixels showed count values expected for tropical forests, as high as 169, or 293.5 K.

The next NOAA overpass over the same site was that of NOAA-10, 4.5 hours after NOAA-11, at about 18:50 local time. Analysis of its channel 3 image indicated only one "warm" pixel with a count value of 77 (see Figure 4a), or 310.2 K using on-board calibration coefficients. No flaming actually existed at the site at the time of this overpass, just smoldering. Channel 4 (10.3–11.3 μm), also recorded for this image, showed only a minor indication of two counts of difference for the hot area. On the day after the fire, 05/September, another NOAA-11 afternoon pass was recorded (63.4°W equatorial crossing at 18:04, or 14:04 local time). Two fire-pixels close to nadir in channel 3 were located at the site of the fire, with counts 8 and 9 (see Figure 4a), corresponding to 321.0 and 320.9 K respectively. They were associated with minor secondary flaming fires, started to

a) ALTA FLORESTA FIRE

04/Sep/89 - N.11@18:15

channel 1

27	27	28	28	28
30	28	29	29	30
34	29	34	35	32
29	30	39	45	46
28	33	51	59	63

channel 2

53	53	53	53	54
55	53	51	52	55
58	53	51	53	56
54	54	54	56	60
55	56	62	63	68

channel 3

123	120	117	116	121
132	109	10	10	97
165	10	10	10	169
126	49	7	109	116
123	113	110	111	104

05/Sep/89 - N.11@18:04

channel 1

41	32	30	31	32
64	53	34	32	37
41	38	34	34	36
33	33	33	38	40
33	33	33	35	40

channel 2

56	55	54	55	56
75	68	55	54	59
52	50	49	54	56
54	53	55	58	60
55	56	56	55	57

channel 3

123	125	126	129	131
93	104	115	107	118
118	66	9	8	126
113	97	126	121	123
126	130	133	131	129

channel 4

95	92	93	96	96
102	99	94	95	98
98	94	93	96	100
94	95	98	100	103
95	97	99	101	103

channel 5

85	83	84	88	88
93	92	87	87	90
88	87	86	89	92
86	87	90	93	95
87	89	92	93	96

04/Sep/89 - N.10@22:54

channel 3

158	158	158	157	158
159	159	144	128	157
162	150	77	92	154
158	153	135	157	159
160	159	161	162	162

channel 4

79	79	79	79	80
79	79	79	79	80
79	79	77	78	80
79	79	79	80	80
79	79	80	80	81

05/Sep/89 - N.11-05:18
No data.
Cloud over fire site.

06/Sep/89 - N.10@11:11
No data.
Cloud over fire site.

06/Sep/89 - N.11@17:54
No fire-pixels detected.

b) JACUNDÁ FIRE

09/Sep/90 - N.11@17:23

channel 1

36	29	24	25	23	25
76	55	26	27	31	27
62	55	30	29	33	27
30	29	22	25	26	45
25	33	34	25	23	25
60	43	42	34	25	25

channel 2

34	30	35	41	41	43
70	50	29	37	47	44
58	50	29	36	47	42
31	30	26	37	44	56
33	40	46	43	41	42
66	52	51	42	38	42

channel 3

110	85	75	72	106	111
93	11	11	11	1	92
143	11	11	11	11	68
114	10	11	11	0	62
83	48	31	70	94	95
67	87	74	80	45	70

09/Sep/90 - N.09@21:44

channel 3

168	168	165	165	166	167
169	166	152	127	161	164
167	168	75	9	134	162
167	171	97	7	149	164
165	163	154	148	157	160
168	161	156	159	159	164

channel 4

90	90	90	89	89	89
90	90	89	89	89	89
90	90	89	88	89	89
90	90	89	88	89	89
90	90	89	89	89	89
90	89	89	89	89	90

channel 5

98	99	98	98	98	99
98	99	98	98	97	99
97	99	97	97	98	99
98	99	98	97	97	99
98	99	98	98	98	99
98	99	98	98	97	99

10/Sep/90 - N.09@09:23

channel 3

172	169	168	168	168	168
174	173	172	170	169	169
169	167	137	133	164	166
168	168	128	9	135	177
172	173	172	162	171	173
175	174	174	173	174	173

channel 4

93	93	93	93	93	93
92	93	93	93	93	92
92	93	93	93	93	93
92	92	92	90	92	93
92	92	92	92	92	93
92	92	92	92	92	92

channel 5

101	101	101	101	101	101
101	101	101	101	101	101
100	101	101	101	101	101
101	100	99	101	101	101
100	100	101	101	101	101
100	100	101	100	100	100

10/Sep/90 - N.10@10:06
No fire-pixels detected.

10/Sep/90 - N.11@17:12
No fire-pixels detected.
Also, clouds in the region.

11/Sep/90 - N.11@18:43
No fire-pixels detected.
Also, clouds in the region.
Site at image border.

FIGURE 4 Digital counts of pixels in AVHRR windows centered at the two controlled fires of Alta Floresta (4a) and Jacundá (4b). Data from six sequential NOAA/AVHRR images are shown for each fire. The time of the overpasses refers to the equatorial crossing, in GMT time. Hot fire-pixels in channel 3 are outlined. All counts in a scale of 256 levels (8-bits).

complete the burning. No indications of hot areas were found in the corresponding images of channel 4 and 5 (11.5–12.5 μm) for this occasion (see Figure 4a). NOAA images were also analyzed for two more days, but showed no indication of hot areas or fire-pixels at the site of the controlled fire.

Another controlled fire took place on 09/September/1990, as part of a larger experiment to evaluate emissions from the burning of Amazon tropical forests

(Ward et al., 1992). The area burned was about 3 km^2 and included primary and secondary forests. The site was in eastern Amazonia, close to Jacundá, some 75 km north of Marabá in the state of Pará, at 04°33′S and 49°03′W. The NOAA-11 afternoon overpass (48.1°W equatorial crossing at 17:23 GMT, 14:23 local time) registered this event when intense flaming occurred throughout most of the site. Twelve fire-pixels in channel 3, just $\sim 14°$ off-nadir and around the image column number 1274, were associated with this fire. Considering the pixel size at this position, ~ 1.35 km^2, an overestimate by a factor of ~ 5 results in relation to the area actually burned. This large factor is caused mainly by the effect of overlap of contiguous AVHRR pixels explained above; if only the distance between the centers of the pixels is used, the fire size is reduced to 2.5 km by 2.2 km, or ~ 5.5 km^2. As shown in Figure 4b, pixel counts in channel 3 for this fire ranged from 0 (saturation) to 11, corresponding to calibrated temperatures of 321.8 K to 320.6 K; surrounding pixels had counts one order of magnitude higher.

The next AVHRR overpass recorded for this second controlled fire was that of NOAA-9, more than three hours later (56.5°W equatorial crossing at 18:44 local time). Some flaming was still occurring, mainly in isolated trunks. Two fire-pixels were detected, with counts 7 and 9, or 320.4 K and 320.1 K, respectively, when calculated through on-board calibration. No significant hot areas were detected in channels 4 and 5 (see Figure 4b). Channel 4 showed a difference of only one count for the fire-pixels, within normal variations for vegetation covers. On the early morning of the next day, 10/September, the descending orbit of NOAA-9 was recorded and its analysis showed one fire-pixel (count 9) at the experiment's site, and again, no strong indication of hot spots in channels 4 and 5 (see Figure 4b). Channel 4 showed a difference of only two counts, also within expected variations for ground surfaces. The next recording of NOAA-10 one hour after, as well as that of NOAA-11 in the afternoon and also on the next day, showed no indications of hot areas in any of the channels.

These two cases further validate the use of the channel 3 thresholding technique to detect fires in tropical forests. They also point to three limitations of AVHRR data in fire detection: evaluation of the size of the areas on fire, estimates of fire temperatures, and lack of information in channels 4 and 5. The overestimate of areas on fire result mainly from the partial overlap of neighbouring pixels, a design characteristic of the AVHRR. In addition, even a small fire with a front of ~ 50 m detected in only one pixel will be largely overestimated because it will be represented by this very pixel, with an area much larger than that of the fire. As shown by theoretical calculations (e.g., Robinson, 1991), a fire with 30×30 m emits enough energy in the channel 3 spectral region to saturate the full pixel. On the other hand, AVHRR also tends to minimize fire detection: only active fires are detected and areas not yet burned or which already burned at the time of the overpass are missed. AVHRR, therefore, can not estimate areas of individual fires.

The temperatures of the fires obtained through channel 3, usually below its saturation limit of ~ 320 K, are a clear indication that the satellite readings are not correct. This same pattern has been reported before for fires in Amazonia (Pereira and Setzer, 1993a) and also for other vegetation types in the world (Setzer and Malingreau, 1993). The only explanation found so far for this unexpected response of channel 3 is that of Setzer and Verstraete (1993) who suggest that a faulty conversion of the sensor signal occurs on-board the satellite. According to these authors, temperatures and radiances higher than the saturation limit of channel 3 are being erroneously allocated to below-saturation levels. And finally, the lack of thermal response observed in AVHRR's channels 4 and 5 for the two cases above impose restrictions on theoretical methods suggesting their use to detect fires and to evaluate temperature or the area of fires (e.g., Matson and Dozier, 1981); similar results were also found for hundreds of fires in different tropical ecosystems (Setzer and Malingreau, 1993).

CONCLUSIONS

The analysis of high and low resolution satellite images presented in this paper showed limitations about uses of remote sensing from space in studies of biomass burning in tropical forests. TM images can provide yearly estimates of the burning of fallen primary forest in new areas of deforestation, but are limited in determining how often a same area is burned in consecutive years or the total area of all surface covers burned each year. These constraints and the acquisition and processing costs per image precludes their use in regular detection, monitoring and mapping of biomass burning, particularly on continental scales when hundreds of scenes are needed.

AVHRR images can monitor biomass burning in tropical forests, but only the location of fires and not their individual size or temperature. Other limitations of AVHRR in biomass burning studies are: fires not actively flaming during satellite overpass, fire fronts smaller than about 50 m, fires under the canopies and not visible to the satellite, presence of clouds or massive smoke plumes in the AVHRR line-of-sight, and solar specular reflection in rare cases. Advantages of their use are: uniform methodology of detection, unrestricted access to images at low cost, availability of at least four images per day, coverage of areas from a few to millions of km^2, precise location of fires, fast real-time capability of monitoring fires, simple and "field-proven" detection algorithm for tropical forests (in the case of channel 3 thresholding of counts), and ease of data access and distribution in real-time.

ACKNOWLEDGMENTS

The analysis of the satellite imagery was made possible with the "Fundacão de Amparo à Pesquisa"—FAPESP grant 90/2950-2. We thank all who participated in the BASE-A and B experiments for their valuable help and support during field work. The INPE/DOP recording of AVHRR images, and the review of the manuscript by A. S. Belward at JRC are also acknowledged.

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