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Abstract. This paper shows the impact of fires in dense forests during the 2005 Amazonian drought. We used rainfall data from the Tropical Rainfall Monitoring Mission (TRMM) and burn scars were mapped using fraction images derived from MODIS MOD09 product. We found that Acre State was the most affected by the drought and its effects on dense forests. However, the combination of drought and intense land conversion practices in Rondônia created a risky environment for fires and consequent carbon losses from ecosystems to atmosphere. Therefore, a complete analysis, including all Amazonian States, would provide useful information for scientists and decision-makers to evaluate and plan the future of Amazonia under possible climate change scenarios.

Palavras-chave: remote sensing, MODIS, TRMM, fires, carbon, Amazonian drought, sensoriamento remoto, queimadas, carbono, seca na Amazonia.

1. Introduction

Recently, some studies have shown that human-induced climate change can reduce rainfall in Amazonia (Cox et al., 2004, Li and Fu, 2006). The projected consequences of this pattern, which was linked to more frequent El Niño events, would be the dieback of Amazonian forests (Cox et al., 2004). However, an increased attention has recently focus on the anomalous warming of the tropical Atlantic sea surface temperatures that is likely to be the causal factor of the 2005 drought (Marengo et al., 2006).

Despite low water availability for plant uptake may have direct impacts on vegetation phenology, physiology, structure and composition, during extremely dry years, one of the most evident aspects, however, is the presence of fire impacts (Cochrane et al., 1999). Very little is known about the extent of fire damage in Amazonian landscapes under extreme drought conditions, which leads to large uncertainties in the Amazonian carbon budget. Moreover, the quantification of tropical dense canopy forests affected by fires is rare. Therefore, in this study we aimed to quantify the intensity and extent of the 2005 drought in terms of rainfall anomalies, using the Tropical Rainfall Monitoring Mission (TRMM) data, and quantify the area of dense forests damaged by fires in 2005 for three Brazilian States (Acre, Rondônia and Mato Grosso). We also attempted to understand the balance between deforestation and drought as the main cause of the forest burnings. Finally, based on literature values, we estimated the potential carbon (C) released to the atmosphere due to pasture and forest fires during the 2005 drought.

2. Methods

The 2005 rainfall anomalies, derived from TRMM data (0.25^{o} spatial resolution), were calculated in terms of standard deviation from the average monthly rainfall (1998-2005), normalized by the standard deviation. The forest and no-forest burn scars mapping was based on image segmentation of the fraction images derived from MODIS MOD09 product, using a non-supervised classification algorithm followed by an image edition procedure for minimizing misclassifications. The INPE´s DETER 2004 dataset was used to identify the land cover types affected by fires (Shimabukuro et al., 2006). We used data from PRODES to evaluate deforestation evolution from 2004 to 2005. Carbon losses to the atmosphere from pastures fires were estimated by multiplying the total burned in deforested areas by the lower (11 Mg C ha^{-1}) and upper (21 Mg C`ha^{-1}) values reported by Kauffman et al. (1998). The same procedure was repeated for the forest area burned. We used a range of forest biomass loss due to fires of 15-140 Mg ha^{-1} (Cochrane et al., 1999) and a conversion factor of 0.5 to obtain the total C released to the atmosphere.

3. Results and Discussion

The strongest rainfall anomalies were observed in the trimester including July, August and September (JAS), during the dry season in the region analyzed. Southeast of Acre and north of Rondônia were the most affected regions by the 2005 drought (**Figura 1a**). This pattern was closely associated to the size and number of burned areas (**Figure 1b**). In Acre, 42% of the total burned area was in forest areas. Rondônia had 40% of the burnings in forests and Mato Grosso 13%. **Figure 1c** shows the southeast of Acre and north of Rondônia in detail.

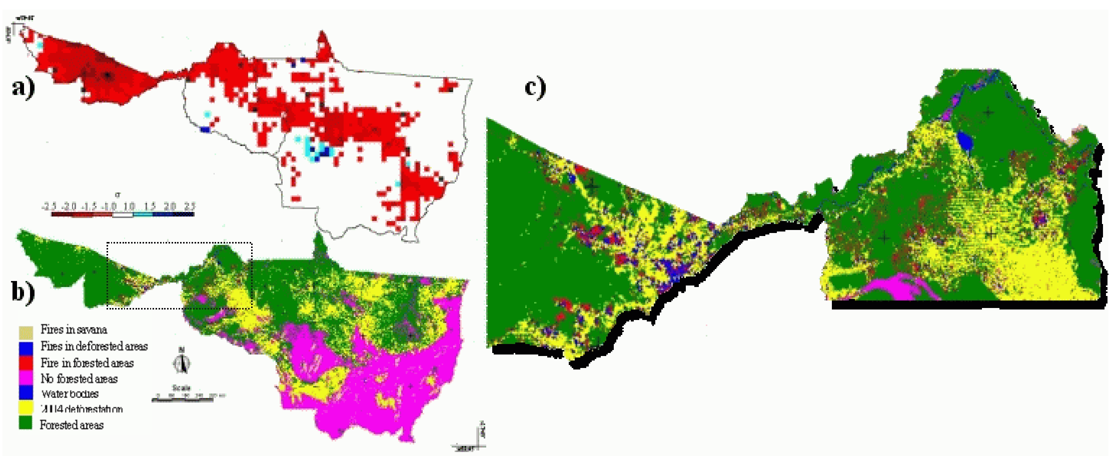

Figure 1. a) Rainfall anomalies (standard deviation) from the average between 1998-2005 derived from TRMM data. Red tones are associated to dryer areas and blue tones to wetter areas. b) Burn scars map derived from MODIS and c) a detail view from the box highlighted in figure b.

The increase of the percent of burned forests followed the rainfall anomalies enhance for all the three States. Interestingly, the rainfall anomalies in Rondônia were much lower (less negative) than in Acre, but the percent of burned forests was almost similar (**Figure 3a**). The trend of increasing the proportion of burned area in the dryer regions (more negative) was much clear for deforested areas than for forest areas (**Figure 3a and 3b**). To better understand the factors that led to the large forest area affected by fires in Rondônia, despite relatively weak rainfall anomalies, we plotted in the same graph the percent of burned areas in forests and the percent difference in deforestation between 2005 and 2004. Acre had 30% reduction in deforestation, even though was the State with higher proportion of forest burned. On the other hand, Rondônia had just a slight decline (~15%) in deforestation, which is still 83% higher than the total deforested area in Acre in 2005 (**Figure 3c, Table 1**). This indicates that while the drought was the main cause of forest fires in Acre, deforestation appeared to be an important factor contributing for the forest fires Rondônia.

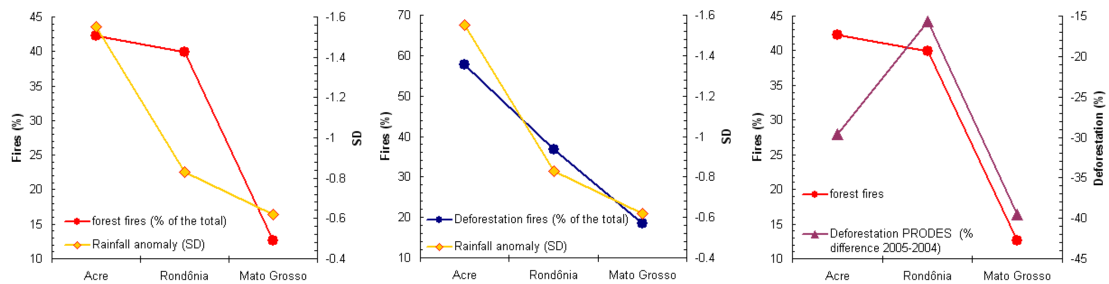

Figure 3. Rainfall anomaly in an inverse scale (more negative is dryer) and a) percent of burned area in forest and b) in deforestation. c) Percent of burned area in forest and percent difference in deforestation between 2005 and 2004, according to PRODES dataset.

In summary, we calculated a total of 15,318 km^2 of burned forests and 17,798 km^2 of fires in previous deforested areas for the three Brazilian States analyzed. The total burned area, including the fires in Cerrado, was 61,536 km^2 (**Table 1**). The values for forests affect by fire in 2005 is within the same order of magnitude of values reported for the El Niño-induced 1997/1998 drought (Barbosa 1998, Cochrane and Schulze, 1998). Contrarily to our analysis, literature values are very localized and do not give a wide perspective of the problem.

Table 1. Summary of the values described in the present study. The percent of total burns is in relation to the total area burned for each land cover and the total burned area include also fires in Cerrado. Dry season length is the number of months with rainfall lower than 100mm. The potential C losses are in Tg per total burned area in deforestation and in forests, respectively. The higher and lower limits are based on the range of values given in the literature.

Burn scars mapping		Acre	Rondônia		Mato Grosso		Total
	Burns in forest (km^2)	3,002	7,942		4,375		15,318
	Burns in deforestation (km^2)	4,110	7,291		6,397		17,798
	Total burned area (km^2)	7,112	19,888		34,536		61,536
	% of total burns in forest	42	40		13		95
	% of total burns in deforestation	58	37		19		113
Deforestation (PRODES)							
	2004 (km^2)	769	3,834		11,814		16,417
	2005 (km^2)	541	3,233		7,145		10,919
	% Difference from 2005 to 2004	-29.64	-15.67		-39.52		-33.49
Rainfall (TRMM)							
	Rainfall anomaly (sd)	-1.55 (0.45)	-0.83	(0.59)	-0.62	(0.64)	
	Dry season length (months)	4.90 (0.46)	4.79	(0.65)	7.37	(3.15)	
Potential C losses in 2005							
Pasture	Lower limit	4.5	8.0		7.0		19.6
	Higher limit	8.6	15.3		13.4		37.4
Forest	Lower limit	2.3	6.0		3.3		11.5
	High limit	21.0	55.6		30.6		107.2
Total	Lower limit	6.8	14.0		10.3		31.1
	Higher limit	29.6	70.9		44.1		144.6

We recognize that this first attempt for estimating C losses to the atmosphere due to fires is certainly over simplified. However, the range of the numbers provides an excellent start line to deal with this problem. The total C losses can be even higher than those reported here because we are not considering emissions from slashed forests and Cerrado. Moreover, we still need to quantify the burned areas for other critical Brazilian States (e.g. Pará). The range of values reported here is mainly related to differences in land use history, such as the number of recurrent burnings in the area. Despite the proportional higher drought impact in forests in Acre, Rondônia appeared to be the State with more forests damaged and with higher C emissions due to fire events. The total values of potential C losses for forests in 2005, between 11.5 Tg C and 107.2 Tg C seem to be consistent with previous reported values. Phulpin et al. (2002) assessing the impact of forest fires in Roraima found a total of 23.2 Tg C emitted to the atmosphere due to the 1997/1998 El Niño drought.

In conclusion, fires have severely affected the forests in Acre during the 2005 drought. Rondônia was the most critical State in terms of absolute forest area damaged and C emissions to the atmosphere. This highlight the fact that the combination of drought events with intense land conversion practices can bring negative consequences for Amazonian forests in the future. We are applying this methodology for other Amazonian states in order to have a more realistic view of this problem and better understand the C budget, ecology and functioning of Amazonia. This will provide useful information for scientists and decision-makers to evaluate and plan the future of Amazonia, as a whole, under possible climate change scenarios.

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