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Satellite Detection of Wildland Fire in South America

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Abstract **-** The identification of hot spots by satellites began in the 1980s locating wildland fires all around the world even in isolated and remote areas. This early detection system can be used for estimating the release of greenhouse gases and subsidize the development of public policy focused on wildfire prevention and nature conservation. Therefore, this study aims to analyse, spatially and temporally, the hot spots detected by the INPE "reference satellites" (NOAA-12 and AQUA_M-T) in all South America for the years 1999 to 2015. A total of 5,052,801 hot spots where analysed. Brazil was the country with the highest hot spot incidence, followed by Argentina, Bolivia, Paraguay, Venezuela, Colombia, Peru, Chile, Equator, Guiana, Uruguay, Suriname and French Guiana. Taking in consideration the size of each country, Paraguay is the nation with the highest hot spots occurrence per area, followed by Bolivia, Brazil, Venezuela, Colombia, Argentina, Equator, Peru, Guiana, Chile, Uruguay, French Guiana and Suriname. In general, the number of hot spots had a small but not significant decrease over the last 13 years. The year of 2004 presented the highest number of hot spots, while 2008 the lowest. A significant growth linear trend in the number of hot spots was detected in Peru and Chile. The month with the most hot spot incidence for South America was September, the least May. Each country presented differences regarding the months with higher and lower wildland fire occurrence mainly due to rainfall patterns.

Keywords**:** Hot spot, wildfire, control burn, Amazonia forest

1. Introduction

Fire is an ancient technique used by farmers for clearing land; reduce pests, diseases, costs and other purposes. Nevertheless, wildland fires (non-structure fire that occurs in vegetation and natural fuels including planned and unplanned fires) can be a major threat to the preservation of biodiversity. They have a direct impact on the fauna and flora and contribute, indirectly, with environmental degradation, leaving the soil more susceptible to erosion while releasing into the atmosphere large amounts of greenhouse gases [1]. The emissions from the 1997–1998 wildland fires in the state of Roraima, Brazil, for example, released into the atmosphere 19,73 millions of tons of carbon [2]. Moreover, the smoke often causes problems for human health, especially respiratory complications and represents, in some locations, a public health issue [3].

New studies indicate that in the second half of this century wildfire potential will increase significantly in South America caused by warming due to climate change [4]. This increase will require new methodologies for preventing fire disasters, also more investments, resources, equipment and labor for fire combat and recovery of damaged areas.

The detection of wildland fires via satellite began in the 1980s [5]. On a global scale, three series of satellites are most used: the National Oceanic and Atmospheric Administration (NOAA), the Advanced Very High Resolution Radiometer (AVHRR) and the Spectroradiometer (MODIS). Images generated by the thermal and infrared sensors installed in these satellites are sent to a control center where they are processed through detection algorithms [5, 6]. It is essential the use of an efficient algorithm, since a hot spot does not mean, necessarily, a wildland fire, but that certain area has a temperature higher than 47ºC [6]. Only after image processing, it is possible to recognize if the hot spot represents a wildland fire, making possible the use of these data for several purposes such as fire fighting, carbon emission statistics, development of preventive activities, scientific papers, and others.

In Brazil, the Weather and Climate Studies Research Center (CPTEC) of the National Institute for Space Research (INPE) generates and provides on their website open access to data from hot spots recorded by satellites and processed by algorithms that indicate wildland fire in South America. Although receiving images from various satellites in operation (NOAA-15, NOAA-16, NOAA-18, NOAA-19, NASA, TERRA, AQUA, GOES-12, GOES-13 and MSG-2), the "reference satellite" is used to compose a time series over the years and thus enable trend analysis focused on numbers for the same periods in regions of interest. From 1999 to August 2007, INPE used the NOAA-12 as the reference satellite, and from then on, the AQUA_M-T. The data from the reference satellite allows analyzes of spatial and temporal trends, since both use the same method and the same time of day to capture the images over the years [7].

Even though the use of satellite for detecting wildland fire has the advantage of wide range and access to remote areas, technical limitations impede the detection of small wildland fires, with line front width usually less than 50 meters. Additionally some situations, such as fires that started and ended during the passage interval of the satellites; presence of dense clouds above the burnt area; surface fire in vegetation with closed canopy; and fire on mountainsides while the satellite only observed the opposite side, restrict the capacity of this technology. Therefore, the number of wildland fires recorded by satellites for a given region corresponds with only a part of the total number [8, 7]. It is important to mention that satellite imagery cannot differentiate the unmanaged and uncontrolled wildfires from the controlled burns [9].

The exact scope of the wildland fire problem in South America is difficult to determine and can only be assessed by satellite data, since there is not a common understanding or definition of what constitutes a wildfire or control burn, and local fire statistics in many cases are incomplete or misleading [10]. Therefore, this study aims to analyze the hot spots detected by the INPE reference satellites in all South America for the years of 1999-2015. The information obtained with this study can be used for estimating the release of CO_2, and subsidize the development of public policy focused on wildfire prevention and nature conservancy.

2. Methodology

2.1. Characterization of the study area

South America is the fourth major continent of the planet with an area of 17,840,000 km^2. It is bordered on the west by the Pacific Ocean, on east by the Atlantic Ocean and on the northwest by the Darién watershed along the Colombia–Panama border. It includes twelve sovereign states – Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, and Venezuela – and two non-sovereign areas – French Guiana, a region of France, and the Falkland Islands, a British Overseas Territory.

There is a wide range of climate conditions on the South America continent and the distribution of vegetation follows annual and seasonal precipitation patterns. Evergreen forest occurs where rainfall is abundant, but savannah, grassland, shrubland and drought deciduous forest become increasingly common as precipitation decreases [11].

South America has the largest area of tropical forests in the world, the greatest amount of biodiversity, and a large reservoir of above and below ground carbon stock [12]. The Guiana Shield (an area that includes all of Guyana, Suriname and French Guiana, and that extends from Colombia and Venezuela in the west to portions of Brazil in the east), in particular, is vastly diverse biologically, being one of the most important centers of species richness on the planet [13].

Nevertheless, the tropical rain forest is under threat. Extensive areas of the Amazon rain forest and the seasonal dry forests of Brazil, Bolivia, Paraguay, and Argentina are undergoing deforestation and conversion to agriculture [14, 15]. The process of forest clearing is usually through cut and burn. Some of these prescribed burns escape the initial planned area and cause additional environmental damage. The increase of agriculture and cattle raising in the area will likely continue causing further land use and cover change in the coming decades [16]. Such extensive land cover change is causing habitat degradation and releasing vast amounts of CO_2 into the atmosphere, therefore aggravating the impacts of global climate change [17, 18]. Climate change, in turn, increases the wildfire potential and consequently, biodiversity lost [4].

2.2. Hot spots data and statistical analysis

Data of hot spots from the INPE reference satellites for the period from 01/01/1999 to 31/12/2015 for all South America countries were obtained from the INPE/CPTEC website. The collected data were categorized according to month and year.

Tukey HDS test was used to check for significant differences between the mean number of annual hot spots recorded per km^2 in the South America countries, and between the mean number of hot spots detected per month. Linear regression trend line was used to assess the expected growth or decline in the number of hotspots in the coming years for all countries. The significance level for all statistical analysis was 5%.

3. Results and Discussion

3.1. Spatial analysis

A total of 5,052,801 hot spots where detected by INPE reference satellites in South America. Brazil had the highest wildland fire occurrence, followed by Argentina, Bolivia, Paraguay, Venezuela, Colombia, Peru, Chile, Equator, Guiana, Uruguay, Suriname and French Guiana. For some countries the data from 1999 to 2002 was missing or corrupted, in such cases the records were not assessed. Only since 2003, all countries presented reliable hot spots data (Table 1).

Table 1: Total annual hot spots detected by INPE reference satellites in South America countries from 1999 to 2015.

Year	Argentina	Bolivia	Brazil	Chile	Colombia	Equator	French Guiana	Guiana	Paraguay	Peru	Suriname	Uruguay	Venezuela
1999	-	22,687	134,603	-	-	-	-	-	17,446	468	-	-	3,851
2000	-	12,371	101,537	-	-	-	-	-	8,259	2,748	-	-	8,340
2001	16,052	10,918	145,567	-	-	-	-	-	11,209	371	-	-	14,813
2002	33,083	33,114	235,792	-	-	-	198	-	25,698	4,358	-	384	15,691
2003	53,385	28,030	235,242	1,969	20,037	1,889	280	1,678	34,040	9,548	585	480	32,608
2004	47,151	47,767	270,384	2,084	21,480	2,209	324	967	23,571	5,245	418	701	19,825
2005	29,965	40,763	240,764	2,285	12,338	2,945	306	816	22,695	10,997	246	399	20,583
2006	34,553	30,165	136,890	1,626	9,370	1,094	188	587	18,284	5,713	277	210	16,549
2007	24,515	36,719	231,252	1,509	17,901	1,354	97	480	25,013	7,828	70	186	19,162
2008	38,677	30,471	123,249	2,537	10,341	907	244	453	14,771	5,943	272	445	17,383
2009	41,627	20,582	123,211	3,254	12,578	3,365	367	1,193	16,093	7,742	670	454	19,069
2010	24,751	66,186	249,291	2,551	11,989	850	166	922	16,753	10,139	279	518	24,001
2011	35,688	28,038	133,087	2,586	8,345	2,423	152	709	18,987	7,430	208	479	11,055
2012	29,588	20,040	193,838	2,852	11,285	1,926	320	1,000	16,293	11,601	532	438	13,262
2013	32,591	16,080	115,220	2,606	11,105	1,705	99	701	22,341	7,733	190	446	21,408
2014	19,726	16,757	183,693	2,640	13,589	1,178	179	1,028	14,609	8,418	361	453	22,323
2015	27,014	22,239	236,371	2,794	15,265	1,095	267	1,484	14,477	11,513	491	1,417	16,590
Mean annual	32,558	28,407	181,764	2,407	13,509	1,765	228	924	18,855	6,929	354	501	17,442

Forest fires occur in South America in a very variable way between one country and another due to natural differences in weather conditions, vegetation, topography, land use, culture and behavior of human populations. Even when analyzing each country separately, these internal differences, especially in the larger countries such as Brazil and Argentina, are responsible for different fire patterns [19].

Using a fire detection algorithm to NOAA–AVHRR images for the period of August 1999–April 2001 in Argentina, Brazil, Paraguay, Uruguay, Bolivia and Chile, [20] detected a total of 2,073,425 wildland fires. Brazil and Argentina had the highest numbers, 84% of the total fires (63 and 21%, respectively), followed by Bolivia 6%, Paraguay 6% and Chile 4%. Data from [10], estimate that during the 1990's about 25.000 wildfires burned a mean annual area of 4.3 million hectares. According to [21] the annual area burned in South America is equivalent to the size of Venezuela. Based on official reports, publications and through informal means, [19] estimated 160,000 annual wildfires in Brazil and 11,513 in Argentina.

Taking into consideration the size of the South America countries, Paraguay was the nation with the highest hot spot occurrence per area, with an annual mean of one hot spot detected for each 22 km^2, followed by Bolivia, Brazil, Venezuela, Colombia, Argentina, Equator, Peru, Guiana, Chile, Uruguay, French Guiana and Suriname (Table 3). According to the classification proposed by [22], Paraguay, Bolivia, Brazil and Venezuela can be classified as countries with "Very High" wildland fire incidence (with 1 hot spot detected by INPE reference satellite per year for each 75 km^2 or less). Using the same classification criteria, Colombia and Argentina can be categorized in the "High" wildland fire incidence category, while Equator, Peru and Guiana in the "Medium" group. Chile, Uruguay, French Guiana and Suriname are ranked in the "Low" category.

Table 3: List of South American countries; their size; mean annual hot spots detected by INPE reference satellites; mean annual hot spots per km^2; area per mean annual hot spot ratio; and classification according to [22]. The countries not grouped with the same letter were statically different regarding the area per hot spot ratio.

Country	Size (km^2)	Mean annual hot spots detected	Mean annual hot spots per km^2	Size area per mean annual hot spots (km^2)	Wildland fire incidence category according to [22] classification
Paraguay	406,750	18,855	0.046	22^{A}	Very High
Bolivia	1,098,580	28,407	0.026	39^{B}	Very High
Brazil	8,511,965	181,764	0.021	47^{B}	Very High
Venezuela	912,050	17,442	0.019	$52^{B,C}$	Very High
Colombia	1,138,910	13,509	0.012	$84^{C,D}$	High
Argentina	2,766,890	32,558	0.012	$85^{C,D}$	High
Equator	283,560	1,765	0.006	$161^{D,E}$	Medium
Peru	1,285,220	6,929	0.005	$185^{D,E}$	Medium
Guiana	214,999	924	0.004	$233^{D,E}$	Medium
Chile	756,950	2,407	0.003	$314^{D,E}$	Low
Uruguay	176,220	501	0.003	352^{E}	Low
French Guiana	91,000	228	0.003	400^{E}	Low
Suriname	163,270	354	0.002	462^{E}	Low

According to [21], the forests in the south of Brazil and east of Paraguay almost disappeared in the last decades due to expansion of soybean cultivation. This process of conversion of forests to agricultural areas is responsible for the increase in the number of wildland fires in the region.

The main ecosystem affected by fire in South America is the Amazon tropical rainforest [23]. The conversion of the Amazon forest into agricultural and pasture areas is the main reason for the high incidence of hot spots in Bolivia, Brazil, Venezuela and Colombia. If deforestation reaches 30%, the Amazonian basin will change to a savannah at the end of the century, with irreversible effects on the regional and global environment, atmosphere and climate [21].

Savannas and shrubland are also highly affected by wildland fires in Brazilan Cerrado, Bolivia, Colombia, and Venezuela. Such fires are account for 13% of the total area burned in South America [23]. Forestry areas with pine and eucalyptus also are constantly affected by wildfires, mostly in Brazil, Chile and Argentina [9; 24; 25].

The low incidence of wildland fires in Guiana, Uruguay, Suriname and French Guiana are mostly linked to the natural vegetation and low rates of deforestation and land-use change. Fires, generally, do not affect well-conserved tropical forests [10]. In Uruguay, due to the vastness of grasslands, wildland fire is not a serious problem [9].

3.2. Yearly temporal analysis

In general, hot spot numbers detected by INPE's reference satellites had a small but not significant decrease over the last 13 years (2003-2015) (r^2 = 0.24; p = 0.09). The year of 2004 presented the highest number of hot spots, while 2008 the lowest. Examining the countries individually, significant linear trend was detected only in Peru (r^2 = 0.54 ; p = 0.001) and Chile (r^2 = 0.41 ; p = 0.02). In both cases indicating an uptrend for the next years (Figures 2 and 3).

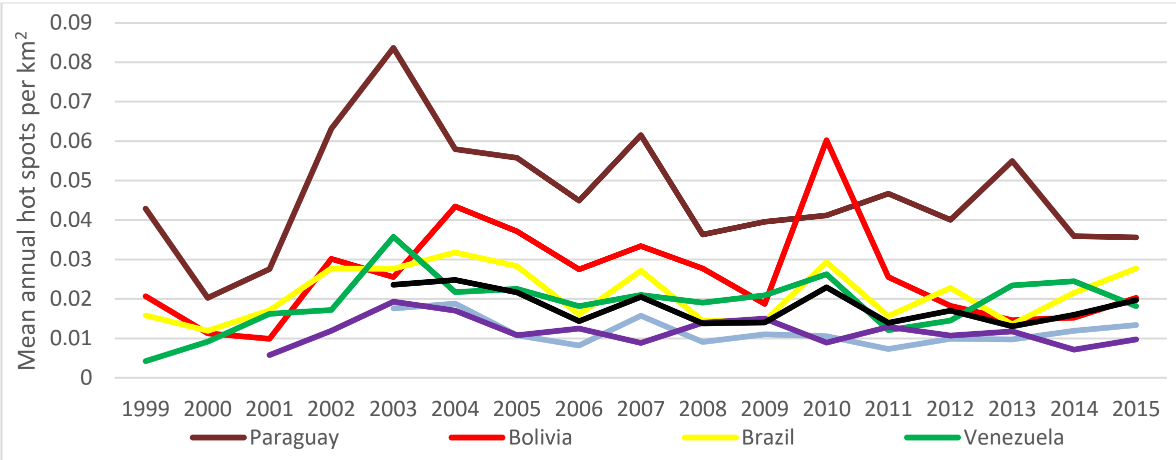

Fig. 1: Mean annual hot spots detected by INPE reference satellites per km^2 in Argentina, Brazil, Bolivia, Colombia, Paraguay, Venezuela and for all South America between 1999-2015.

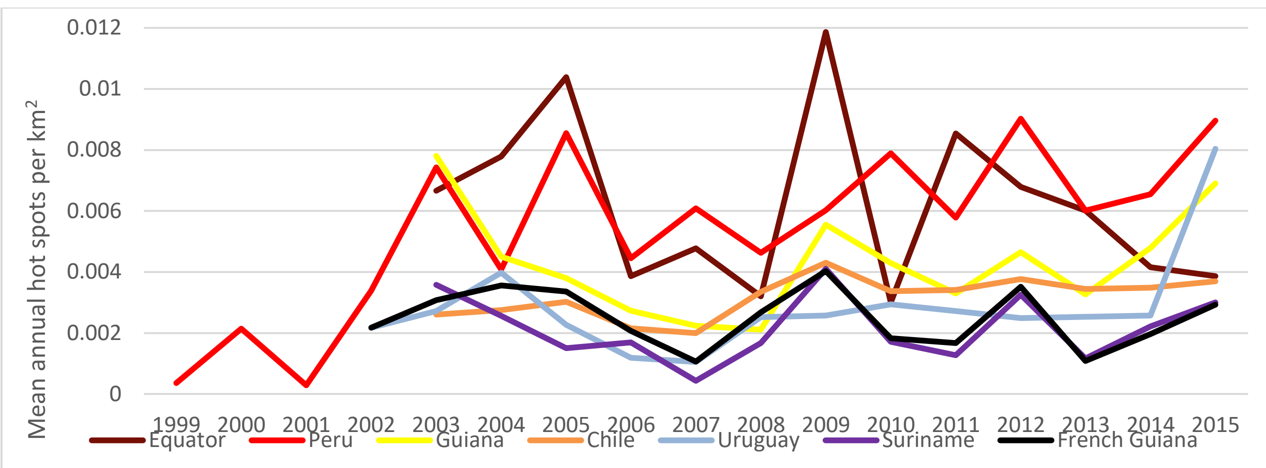

Fig. 2: Mean annual hot spots detected by INPE reference satellites per km^2 in Chile, Equator, French Guiana, Guiana, Peru, Suriname and Uruguay between 1999-2015.

The annual changes in wildland fire occurrence are mostly due to human behavior linked with climate variations caused by El Niño and La Nina [23]. The El Niño alters rainfall patterns and intensifies drought in some South America regions leaving the vegetation dryer and more prone to burn. Recent studies proved the relation between El Niño and interannual fire activity [26, 27, 28]. On the other hand, La Nina causes an increase in rainfall in some South America regions.

El Niño events occurred in South America with low and moderate intensity in the years of 2003, 2004 and 2010 [29], and are likely responsible for the large number of hot spots detected during those years. La Nina occurrences in 2008 and 2011 are likely responsible for the reduction of wildland fires during these years.

3.3. Monthly temporal analysis

The record month of hot spots in South America was September, followed by August, October, November, July, December, March, February, January, June, April and May. These results are in agreement with [20] who affirms that most of the fires in southern South America occur during late winter and spring (August–December). According the same author, during 1999–2001 the summer and early autumn wildland fires (January–April) represent 35% of the total, more than twice of the number found in this study (14%).

Each country presented differences regarding the months with the highest and lowest fire occurrence, with the highest months always during the dry season. Brazil, Bolivia, Paraguay and Peru, for example, had their highest wildland fire occurrence in the month of September. Several authors [e.g. 1, 20, 24, 25, 30] affirm that the fire season in Brazil lasts from July to December, with the peak in the months of August and September. [31] Also states that August and September are the months with the highest wildland fire occurrence in Bolivia. In Paraguay and Peru the highest occurrence goes from June to November [32, 33].

The month with the highest hot spot incidence in Argentina and Uruguay is August, a little earlier than most South America countries. In Argentina, as in Brazil, the wildland fire season varies among different regions due to their large size. In Argentina southern territories where the rainy season occurs in winter, the wildfire season starts in late spring and last until early summer. In northern states and in Uruguay, fires tend to occur in autumn and winter [9, 34].

In Chile and Venezuela, the month with the highest number of hot spots was March, which is one of the driest months in both countries. According to [9, 35] the dry season in Chile lasts from November to April and the wildfire season occurs from October to April. In Venezuela, the fire season is from December to April and wildfires occurs mostly in the eastern portion of the country where forests are being cut down to give place to agriculture [9, 36].

In French Guiana, Guiana and Suriname there is little published information about wildland fire occurrence. Their month with the highest hot spot occurrence is October. These countries have a short dry period in March and a long dry period from August to November with dry severity varying from year to year. According to [37] some long dry periods remain mild with 50–100 mm precipitation each month, whereas some dry periods are severe with 4 months with less them 50 mm.

Colombia presented the highest hot spots recorded in February and Equator in November. According to [10], fires in Equator occur mainly in autumn and winter, while in Colombia mainly from January to May, as well as in November and December.

Table 2: Monthly mean number of hot spots registered by INPE reference satellites per year in South America countries. The months for each country not grouped with the same letter are statically different.

Country	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Argentina (2001-2015)	1,811^{B,C,D}	1,402^{C,D}	1,365^{C,D}	890^{C,D}	489^{D}	818^{C,D}	2,726^{B,C}	**8,184^{A}**	8,148^{A}	3,841^{B}	1,938^{B,C}	945^{C,D}
Bolivia (1999-2015)	134^{C}	107^{C}	102^{C}	134^{C}	245^{C}	481^{C}	1,595^{C}	7,962^{A,B}	**10,604^{A}**	5,370^{B}	1,371^{C}	302^{C}
Brazil (1999-2015)	2,600^{D}	1,550^{D}	1,724^{D}	1,437^{D}	2,354^{D}	5,661^{D}	10,306^{C,D}	39,322^{B}	**56,167^{A}**	34,076^{B}	17,457^{C}	9,109^{C,D}
Chile (2003-2015)	265^{C}	235^{C,D,E}	**718^{A}**	435^{B}	253^{C,D}	61^{F}	32^{F}	46^{F}	78^{F}	97^{E,F}	71^{F}	117^{D,E,F}
Colombia (2003-2015)	2,423^{B}	**4,032^{A}**	3,546^{A,B}	478^{C}	130^{C}	135^{C}	288^{C}	514^{C}	507^{C}	395^{C}	417^{C}	645^{C}
Equator (2003-2015)	53^{D}	32^{D}	17^{D}	17^{D}	12^{D}	21^{D}	33^{D}	101^{C,D}	196^{B,C,D}	280^{B,C}	**672^{A}**	332^{B}
French Guiana (2002-2015)	3^{C}	1^{C}	2^{C}	2^{C}	1^{C}	0.1^{C}	0.2^{C}	4^{C}	42^{B}	**125^{A}**	44^{B}	786
Guiana (2003-2015)	81^{B,C,D}	70^{B,C,D}	108^{B,C}	96^{B,C,D}	19^{C,D}	4^{D}	6^{D}	18^{C,D}	107^{B,C}	**220^{A}**	130^{A,B}	66^{B,C,D}
Paraguay (1999-2015)	853^{B,C}	752^{B,C}	897^{B,C}	584^{C}	255^{C}	383^{C}	1,005^{B,C}	5,047^{A}	**5,337^{A}**	2,185^{B}	1,066^{B,C}	492^{C}
Peru (1999-2015)	132^{D}	112^{D}	48^{D}	44^{D}	70^{D}	113^{D}	394^{C,D}	1,993^{B}	**2,688^{A}**	891^{C}	349^{C,D}	97^{D}
Suriname (2003-2015)	12^{C,D}	10^{C,D}	24^{B,C,D}	15^{B,C,D}	4^{D}	0.4^{D}	1^{D}	8^{D}	53^{B,C}	**153^{A}**	59^{B}	15^{B,C,D}
Uruguay (2002-2015)	39^{A,B}	13^{B}	33^{A,B}	33^{A,B}	39^{A,B}	41^{A,B}	51^{A,B}	**75^{A}**	67^{A,B}	32^{A,B}	37^{A,B}	40^{A,B}
Venezuela (1999-2015)	2,854^{B,C}	3,573^{B}	**5,155^{A}**	2,162^{C,D}	786^{E}	186^{E}	160^{E}	219^{E}	342^{E}	422^{E}	533^{E}	1,050^{D,E}
South America (2003-2015)	11,894^{D,E}	12,560^{D,E}	14,632^{D,E}	6,917^{E}	4,822^{E}	7,678^{E}	17,711^{D,E}	65,593^{B}	**92,746^{A}**	49,025^{C}	24,959^{D}	14,019^{D,E}

4. Conclusion

Although there are already several published studies trying to quantify wildland fire occurrence in South America, this presents an impartial methodology using only data from reference satellites that use the same method and the same day time to capture the images over the years. The data obtained with this study allows analyzes of spatial and temporal trends, thus contributing to a better understanding about wildland fires in South America.

Based on the results obtained, Brazil is the country with the highest wildland fire occurrence in all South America, followed by Argentina, Bolivia, Paraguay, Venezuela, Colombia, Peru, Chile, Equator, Guiana, Uruguay, Suriname and French Guiana. Percentage wise, Paraguay is the nation with the highest hot spot occurrence per area, followed by Bolivia, Brazil, Venezuela, Colombia, Argentina, Equator, Peru, Guiana, Chile, Uruguay, French Guiana and Suriname.

In general, the number of hot spots detected by INPE's reference satellites had a small but not significant decrease over the last 13 years. The year of 2004 presented the highest number of hot spots, wile 2008 the lowest. A significant growth linear trend was detected in Peru and Chile.

The month with the most hot spots record for South America was September, followed by August, October, November, July, December, March, February, January, June, April and May. Each country presented differences regarding the months with the highest and lowest wildland fire occurrence. Brazil, Bolivia, Paraguay and Peru, for example, had their highest fire occurrence in September; Argentina and Uruguay in August; Chile and Venezuela in March; French Guiana, Guiana and Suriname in October. Colombia presented the highest hot spots recorded in February and Equator in November.

Future studies that address the differences in the wildland fire occurrence in different regions and states of each country, especially those with large territorial extension, are recommended in order to obtain more accurate data at a lower spatial resolution.

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