An assessment of burned area/drought relationship from global remote sensing in Brazilian biomes

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Abstract. Fires are complex processes having important impacts on ecosystem functioning with societal consequences, especially in Brazilian biomes. The fire activity is determined by complex feedbacks between climate and vegetation types, which respond differently to water deficit. Fire danger indices (FDI) based on daily meteorological information are used as proxies for fuel flammability. In this study, we evaluated the performances of the most used FDI at main Brazilian biomes (Amazonia Forest, Atlantic Forest, Cerrado, and Caatinga) using global remote sensing burned area (BA) products. We computed 12 FDI using meteorological CRU-NCEP dataset at 0.5° resolution from 2002 to 2011. The land cover was evaluated using a fuelbelds map and the monthly BA from the MCD45A1, ESA Fire Cci, GFED4 and GFED4s datasets. Each FDI/BA relationship was computed using R^2 and evaluated with Principal Component Analysis (PCA).We applied a general linear model (GLM) for main PCA axes to predict fire occurrence per biome. All FDIs and BA showed good relation (R^2 >0.8), except for SPEI (R^2 < 0.2). FDIs with highest soil field capacities showed the best correlation for Cerrado and Caatinga and the FDIs for shallow soil to the Brazilian tropical forests. The GLM showed highest accuracy (>50%) to predict the fire occurrence in the Amazonia and Cerrado. These results suggest that FDIs are biome-specific to explain the seasonal course of burned in Brazilian biomes, and that global burned area products from remote sensing are consistent to each other. Selected FDIs should be used for fire danger forecast in each biome.

Keywords: fire regime, sensor, fire index, fuel limited, drought limited, water balance
Palvaras-chave: regime de fogo, sensores, combustivel-limitado, clima-limitado, balanço hidrico

1. Introduction

Fire are abiotic events important on many ecological processes and landscape dynamic in fire prone biomes, altering the species density and composition and releasing greenhouse gases to the atmosphere (Pausas and Keeley et al., 2014). In other, fire is used in land cleaning to agricultural activities and its uncontrolled used can cause severe impacts on the environment and the human society, especially in developing regions as Brazil (IPCC, 2014).

Fire occurrence is driven by different constraints between weather conditions and fuel resource availability (Hoffmann et al., 2012), where microclimate have effects for flammability of tropical vegetation, mostly through drought events controlling the fire season. Dryer conditions tend to increase fire activity in non-fuel-limited ecosystems, such as wet tropical forests, where the abundant fuel amount due high annually vegetation productivity not limit the fire spread, but the regular and constant rainfall limit the length of the fire season (climate limited) (Stott, 2000). In contrast, in grasslands, savannas and xeric shrublands, the growing period preceding the dry season tend to modulate the fire activity by affecting the accumulation of fine fuels (fuel limited) (Krawchuk and Moritz, 2011).

Different approaches have been developed to estimate the potential fire risk using various indices nondestructive measures to evaluate the fuel stand's proneness to fire in terms of weather conditions. These drought indices are widely used in fire management activities in global official warning systems, with few efforts performed to Brazilian ecosystems due to the lack of consistent spatial data in specific areas on vegetation hydrological status and fire occurrence. In this context, the use of the climate-based fire danger indices (FDI) related to burned area (BA) datasets derived from global remote sensing, which are increasingly used efficient tools for the global monitoring fire risk and fire emissions estimates (Mouillot et al., 2014) can be a potential alternative to fire assessments in Brazil. So, we propose here to evaluate the most used drought indicators o estimate the potential fire danger in main biomes over Brazil, testing their consistency across the global burned products.

2. Methodology

2.1. Study area and land cover dataset

This study area covers the four main biomes (Amazonia, Atlantic Forest, Cerrado and Caatinga) (Figure 1) over Brazil, which extends from -5.28°N to -33.77°S and from -73.85° W to -34.82°W, with area about 850 millions of ha. Amazonia is wet tropical forest with a fire occurrence usually associated with extreme drought events and with an increasing number of human-induced ignitions due to deforestation to expansion of the agriculture frontiers (Allencar et al., 2011). The Atlantic Forest is a mix of broadleaf forest to grasslands forests with fire activity generally human-induced from logging activities, leading this biome to vulnerable to secondary fires (Joly et al., 2014). Cerrado is a mosaic of grasslands to open shrublands, with different tree cover, altitude and climatic gradients. The fire is an intrinsic recurrent disturbance in this biome and human-used for land clearing and renewal of pastures to agricultural activities (Stott, 2000). Caatinga is annually marked by high annually temperatures and severe drought, but due to low vegetation productivity in the rainy season, fire is mostly used for land clearing after cutting of existing vegetation (Goldammer et al., 1990).

We used land cover over to spatial distribution per Brazilian biome (MMA, 2016) using the fuelbelds map from Pettinari et al. (2014) at 300m spatial resolution. We rescaled this map at 0.5° spatial resolution and the land cover classification of Tropical/Subtropical Wet Broadleaf Forest, Tropical/Subtropical Dry Broadleaf Forest, Tropical/Temperate Grasslands, Savannas and Shrublands and Desert/Xeric Shrublands correspond respectively to Amazonia, Atlantic Forest, Cerrado and Caatinga vegetation over Brazil (Figure 1).

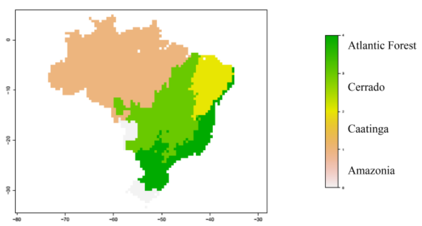

Figure 1 - Spatial distribution of main fire prone biomes over Brazil. The colors indicate Tropical/Subtropical Wet Broadleaf Forest (Amazonia, pink), Xeric Shrublands (Caatinga, yellow), Tropical Grasslands, Savannas and Shrublands (Cerrado, light green) and Tropical/Subtropical Dry Broadleaf Forest (Atlantic Forest, dark green) (adapted from Pettinari et al., 2014 and MMA, 2016)

2.2. Meteorological fire danger indices (FDI)

We computed 12 FDI using global daily gridded meteorological variables compiled in the CRU-NCEP v5.3 dataset (available at http://dods.extra.cea.fr/data/p529viov/cruncep/) at 0.5° and six hours of spatial and temporal resolutions, respectively, from 2002 to 2011. These FDI were computed on a daily time step according to equations synthesized in Table 1, which

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perform the potential fire risk to vegetation from soil moisture deficit: KBD, FFDI, Linacre, SPEI , I , NI , MNI, Zh; or fuel moisture: FWI components (FFMC, DMC, DC) and FMI. We performed the Linacre index for field capacities of 100, 250, 550 and 750mm to cover the soil type variabilities for shallow soils to very deep soils. We used the 'fwi.fbp' library (Wang et al, 2014) from R program (https://CRAN.R-project.org/) to compute the FWI components and we downloaded the SPEI index in the same spatial resolution from 1 to 48 months directly in SPEI database (http://sac.csic.es/spei/). All daily values were then averaged on a monthly time step.

Table 1. Overview of meteorological fire danger indices (FDI) and their input meteorological variables

Meteorological FDI	**Formula**	**References**
McArthur Forest Fire Danger Index (FFDI)	$FFDI_t = 2e^{-0.45+0.98\ln DF_t - 0.0345 RH_t - 0.0338\, Tmax_t + 0.0234\, w_t}$ $DF = \frac{0.191\, x\, (I+104.0)\, x\, N^{1.5}}{(3.52\, x\, (N+1)^{1.5}) + R - 1}$	McArthur, 1967
Fine Fuel Moisture Code (FFMC)	$FFMC = 101 - m$	Van Wagner, 1987
Duff Moisture Code (DMC)	$DMC = 244.72 - 43.43\ln(m-20)$	
Drought Code (DC)	$DC = 400\ln\frac{800}{Q}$	
Angstrom Index (I)	$I_t = \frac{RH_t}{20} + \frac{27 - Tmean_t}{10}$	Chandler, 1961
Keetch-Bryam Drought Index (KBDI)	$KBDI_t = KBDI_{t-1} + DF_t$ $DF = \frac{203.2 - KBDI_{t-1}\, x\, 0.968\, x\, e^{(-0.0875\, Tmax + 1.5552)} - 0.0083}{1 + 10.88\, x\, e^{-0.001736\, R}}$	Keetch-Bryam, 1968
Nesterov Index (N I)	$N\, I_t = \sum_t^N N\, I_{t-1}\, Tmean\, x\, D_t$ $D = Tmean - Tdew$ For prec under 3 mm/day	Nesterov, 1949
Modified Nesterov Index (MNI)	$MNI_t = K\, x\, N\, I_{t-1}$	Verevesky et al., 2002
Standardized Precipitation Evaporation index (SPEI)	$SPEI_i = p_i - ETO_{PMi}$	Vicente-Serrano et al., 2010
Zhdanko Index (ZH)	$ZH_t = k\, ZH_{t-1} - D_t$ $D_t = Tmean_t - Tdew_t$	Zhdanko, 1965
Sharples Index (FMI_KBDI)	$FMI_t = KBDI_t\, x\, \frac{max(1, w_t)}{10 - 0.25(Tmean_t - RH_t)}$	Sharples et al., 2009
Linacre Index (LINACRE for 100, 250,	$LINACRE_t = \frac{W_t}{fc}$	Linacre, 1973

550 and 750 mm of soil field capacity)	$W_t = min(fc, W_{t-1} - ETP_t + prec_{t-1})$ $ET_t = min(AET\, x(\frac{W}{fc})^2, ETP_t)$

* N = number of days since last rain; R = average annually precipitation (mm); t= time in days; i= time in months aggregated at different time scales; Tmax=maximal temperature (°C); Tmean= mean temperature (°C); w= average wind speed measured at height of 10m (m.s^{-1}); Tdew= dew point temperature (°C); m= daily fuel moisture ;D= dew point deficit; RH= relative humidity (%); prec= total daily precipitation (mm); ET0_PM= evapotranspiration rate of Penman Monteith model (1968); k is a scale coefficient that controls the index change when precipitation occurs on day N. This reduction factor is equal to 1 when no rainfall occurs, is equal to 0 when daily rainfall is 20 mm or more, and gradually decreases between these thresholds; fc= soil field capacity (mm); W= soil water content (mm) which is total saturated field capacity to initial time in first day of year; AET= maximal evapotranspiration (mm.day^{-1})

2.3. Burned area datasets

We used four monthly global remote sensing burned area (BA) datasets (MCD45A1, GFED4, GFED4s and ESA FireCci) (Table 2) from 2002 to 2011 and at 0.5° spatial resolution. For this study, we rescaled GFED4s and GFED4s data to 0.5° spatial resolution on the same monthly basis.

Table 2. Description of main global burned area datasets used in this study

Global BA dataset	Satellite/Sensor	Spatial and temporal resolutions	References
MCD45A1	Modis/ Terra, Aqua	0.5°, 2000-present	Roy et al., 2008
GFED4	Modis/TRMM,VIRS, ATSR	0.25°,1995 -present	Giglio et al., 2013
GFED4s_BF	Modis/TRMM,VIRS, ATSR, Terra,Aqua	0.25°,1995- present	Randerson et al., 2012
ESA FireCci	Envisat/Meris	0.5°, 2002-2011	Chuvieco et al., 2016

2.4. Data analysis

We evaluated the linear relationship between the monthly values of each FDI and BA dataset using the coefficient of determination (R^2) by grid cell. Then, we performed a Principal Component Analysis (PCA) where individuals are grid cells and the R^2 values as variables obtained from monthly FDI/BA relationship. Finally, we computed a general linear model (GLM, equation 1) where the biome map is function of the PCA axis 1, 2 and 3 to assess whether the FDI/BA relationships were biome specific.

$$VEG = a\,PC\,1 + bPC\,2 + cPC\,3 + e \quad (1)$$

where VEG indicate the vegetal type, PC 1-3 the axes from 1 to 3 from principal components analysis, a, b, c= slope of linear regression

3. Results and discussion

3.1. Sensitivity of the seasonal FDI/BA relationship to BA datasets

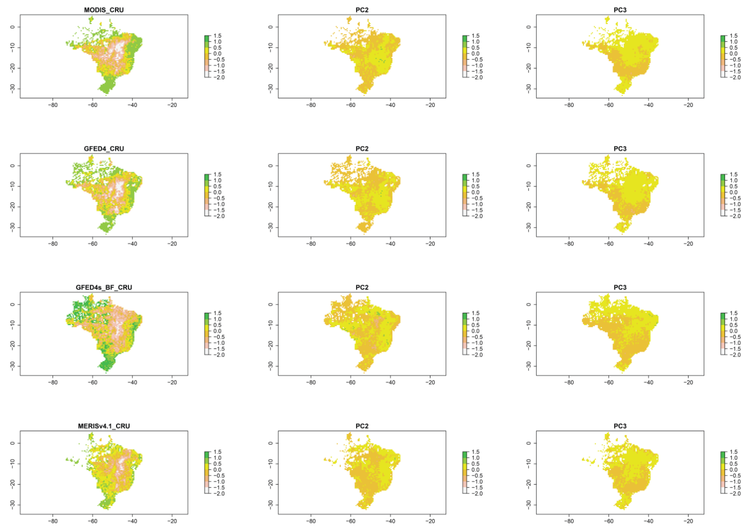
All FDIs showed good correlations (R^2) with BA for all datasets (MCD45A1, GFED4, MERIS and GFED4s), except for SPEIs ($R^2 < 0.2$). The highest R^2 values were founded mainly in the central region of Brazil ($R^2 > 0.8$) with a consistent result for all BA datasets. Better correlations however could be observed for GFED4s including small fires outside this central region. The three first principal components (PC 1-3) showed an overall explained variance higher than 95% for all BA datasets. PCA coordinates higher than 0.5 for axis 1 were found on the south, northeast and north regions of Brazil, while PCA1 axis values were lower than -0.5 for the central region for all BA datasets (Figure 2A).

When looking at the variable map (Figure 2B) for this PCA1 axis, negative values correspond to the highest correlations between FDIs and BA, except Linacre indices for soil field capacities 550mm and 750mm, suggesting that the seasonal BA in the central region is highly correlated to most of the drought indices, while other regions are the less correlated. Regarding PCA axis 2, positive values were observed for the eastern central region, the north, and part of Amazonia, while negative values were observed mostly for the southern regions, illustrating the high correlation of BA with Linacre indices for deep soils on positive values of the PCA2 axis, while other regions would be more correlated to FFMC or ZH indices.

Our analysis could show a good consistency of the FDI/BA relationship across different BA datasets. However, the better correlations FDI/BA were observed using GFED4s including small fire, mostly for the most fire prone area Cerrado, but particularly for the Amazonia where correlation coefficients obtained for most BA datasets are below 0.3, while they reach values higher than 0.5 for GFED4s. This suggests that the fire regime in this not much fire-prone area, as a consequence of high air humidity and high soil water content along the year, is less well correlated to drought by the conventional large fire datasets. Small fires seasonal pattern would be more correlated to the drought pattern.

The use of FDIs to estimate the fire occurrence and fuel interaction has also been performed in different ecosystems from developed countries (Aparci et al., 2013; Abatzoglou and Kolden, 2013) but these low efforts considered the validations from BA datasets or the use of FDI specific to represent the hydrological process for each vegetation type (Williams et al., 2015).

A



B

Figure 2 A- Three principal components axes (PC 1-3) from Principal Components Analyses (PCA). The PCA was performed from coefficient of determination (R^2) between burned area (BA) datasets (MODIS, GFED4,

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GFED4s_BF and MERIS) and all fire meteorological danger indices (FDI) computed from satellite climate dataset (CRU-NCEP) at 0.5° of spatial resolution from 2002 to 2011. **B-** Eigenvalues from two first principal axes (Comp. 1-2) for each BA dataset and all FDI. The FDI evaluated are McArthur index (FFDI), Duff Moisture Code (DMC), Drought Code (DC), Fine Fuel Moisture Code (FFMC), Swedish Angstrom index (I), Keetch-Bryam Drought Index (KBDI), Russian Nesterov Index (NI), Russian Modified NI (MNI), Standardized Precipitation-Evapotranspiration Index (SPEI) from 1 to 48 months of drought (SPEI01-48), Zhdanko index (Zh), Australian Sharples Fire Weather Index (FMI_KBDI) and Linacre index with 100-750mm of field capacity (Linacre_100-750)

3.2. Biome specific FDI/BA relationship

In general, the GLM with the three first main PC axes showed probabilities (>50%) to accurately predict the BA in the Amazonia and Cerrado with no major discrepancies between BA datasets. Lower prediction probabilities (<32%) were observed in the Atlantic Forest and Caatinga (Figure 3). For Amazonia and Cerrado, these results were higher for larger fire BA products from MODIS (70%), MERIS (69%) and GFED4 (63%) than the BA product including small fires GFED4s (53%). In the Atlantic Forest, the MERIS dataset showed higher values (31%) than other BA datasets. All BA datasets showed low probabilities in the Caatinga (30%).

Our results showed that FDIs were able to reproduce the constraint of climate/fuel moisture in the control of fire activity in the main Brazilian vegetation types, with a better correlation obtained for dry ecosystems. In wet tropical forests the fuel is always available for burning during the fire season due the high annual net productivity primary, so the fuel moisture conditions is more a limiting factor of fire activity (Krawchuk and Moritz, 2011). In these ecosystems, the vegetation functioning and adjustment physiological processes to drought tend to reduce the water loss, but the air dryness associated to drought events or temperature heat waves have an important role in the climate regulation and soil water, which influences the drying of live and dead fuels (Stott, 2000). The soil moisture estimated by FDI with high soil field capacity (i.e. 750mm in the Linacre indices, mainly) and taking longer time to desiccate were more efficient to explain the fire pattern.

In contrast to this non fuel-limited ecosystems, the driest ecosystems in Brazil (i.e. deserts, xeric shrublands) or seasonally dry (i.e. grasslands, savannas/Cerrado, shrublands) ecosystems can be fuel limited so the primary production in the wet growing season preceding the fire season can affect the fuel resource able to burn (Stott, 2000). For Cerrado, we observed that better correlations were obtained for NI, DC, and the Linacre_100mm which represents the moisture content of the surface litter and fine fuels, dew-point deficit and the soil deficit for shallow soils (less 200mm of soil depth), respectively. As main combustible fuel in the Cerrado consists of grasses and other ground-layer in their different physiognomies (Pivello, 2011), our results suggest that in these ecosystems the fire activity increases with a rapid drying of grasses or herbaceous fuel. Good correlations between fire occurrences were also observed with FFDI index (Hoffman et al., 2012) in Cerrado. The model used in this study weakly explained the fire occurrence in Caatinga. This region is typically dry and the low annual rainfall and high evapotranspiration rate might induce low climate response. The burned area is low, so the remote sensing signal might inaccurate or fuzzy, and the rare fire settings might be fully driven by human settings rather than climate.

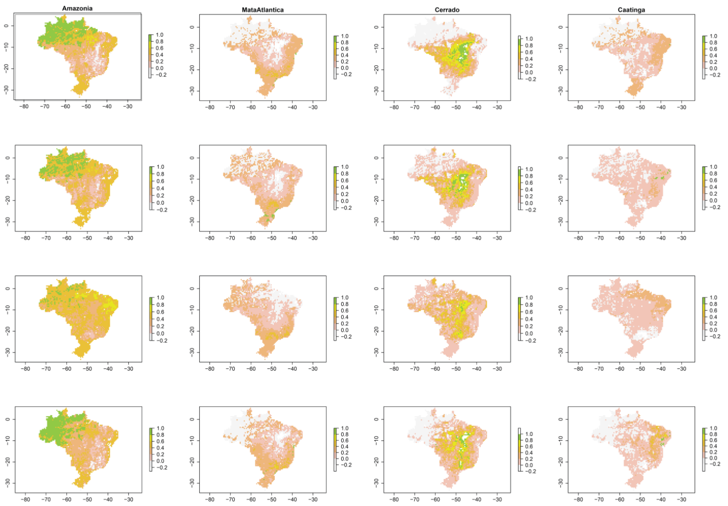

Figure 3. Probability maps of biome (Amazonia, Forest Atlantic, Cerrado and Caatinga in column) distribution obtained from a General Linear Regression Model based on the three main principal axis (PC) of the PCA performed on the FDI/BA relationship for each BA dataset (MODIS, GFED4, GFED4s and MERIS ordered by line)

4. Conclusion

In this study, we showed that FDIs computed from empirical water balances considering the lower soil capacity are more correlated to the pattern of fire occurrence in the Cerrado biome and FDIs from deep soil are more correlated in Amazonia and the Atlantic forest. So using a panel of drought indices and different burned area databases provided useful information to understand the burned area fire occurrence pattern in the contrasted vegetation types covering Brazil.

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